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## PREFACE.

SINCE the foundation of the Carnegie Research Scholarships in 1900, the reports on the research work carried out by holders of the Scholarships have been published in the *Journal of the Iron and Steel Institute*. For the first three years it was possible to do this without increasing the ordinary number of the volumes of proceedings, but in 1904, in order to prevent these from becoming too unwieldy, it became necessary to issue a supplementary volume. In 1905 the reports were again printed in the ordinary volumes of proceedings, but from 1906 onwards they have always been published in a separate volume, which formed nevertheless one of the regular series of the *Journal of the Institute*.

This year the Council has ordered that the reports of the Carnegie Scholars shall henceforth be published under a title that will differentiate them from the *Journal* containing the Proceedings. The present volume, therefore, constitutes the first of a new series appearing under the title "Carnegie Scholarship Memoirs."

The memoirs in this volume are six in number. For that entitled "A Contribution to the Study of the Special Ternary Steels," the author, Mr. Albert M. Portevin (Paris), received the Carnegie Gold Medal. The reports of the other five holders of scholarships, Mr. W. Giesen (Mexico), Dr. E. Preuss (Darmstadt), Mr. E. A. Wraight (London), Mr. L. P. M. Révillon (Paris), and Mr. T. Baker (Llanelly), have been deemed by the Council to be of sufficient merit to justify their publication in full.



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# I.

## THE SPECIAL STEELS IN THEORY AND PRACTICE.

BY WALTER GIESEN (MONTEREY, MEXICO).

### I. THE INFLUENCE OF NITROGEN ON STEEL.

WITHIN a relatively short time, the advances made in metallography have attained high importance in connection with the manufacture of steel, and particularly as regards the production of special steels. By the aid of metallography the makers and workers of iron and steel, and also the merchants dealing in these products, are afforded a scientific explanation of the structure of iron and the metallic alloys.

Metallographical examination is intended to supplement the results obtained by thermal treatment, not merely by the microscopical examination of suitably prepared sections, but also by affording information as to the causes of the micro-structure observed and identified.

Metallography enables failures in practice to be investigated in accordance with certain accurate rules, improvements to be suggested, and the causes of these failures to be ascertained. It should therefore undoubtedly be applied in practice, and definite standards should be laid down for the method of carrying out metallographical control determinations.

It is a well-known fact that steels of practically the same composition exhibit great differences in hardness, tensile strength, and other physical properties when manufactured in different ways. Thus, Bessemer basic steel is milder than Bessemer acid steel, and basic open-hearth steel milder than acid open-hearth steel.

In many instances this great divergence in the physical properties of steel is attributable to the percentage of nitrogen



present, the influence of which element has, unfortunately, not yet been sufficiently appreciated. More especially in the case of hardened steels does nitrogen exert an influence that must not be under-estimated. The mechanical properties of steel vary considerably with different proportions of nitrogen. In the case of mild iron the tensile strength increases with the nitrogen content, whilst the elongation diminishes. If the proportion of nitrogen in ordinary steel be raised from 0.037 per cent. to 0.041 per cent., the elongation disappears entirely, and the steel becomes quite brittle.

The critical nitrogen content lies between 0.037 and 0.041 per cent., that is, the point at which elongation completely disappears. In the course of a number of examinations of ordinary steels, the author has found the critical limit to be 0.039 per cent. of nitrogen. This critical nitrogen content depends largely on the percentage of carbon in the steel, and this connection is probably the reason why hard steels are more readily rendered brittle than mild grades, the critical nitrogen content of the former being higher than that of the latter. The influence of nitrogen on the magnetic and electrical properties of iron and steel is unimportant, beyond the fact that it increases hysteresis and coercive force in specially mild iron.

Metallographical and micrographical examinations conducted by the author have shown that the nitrogen in iron is combined exclusively with ferrite, and that no trace of it can be detected in the carbides. In hardened steel it occurs in martensite.

White pig iron usually contains more nitrogen than grey pig. When pig iron is remelted in the cupola furnace, the nitrogen content is increased; and in the open-hearth furnace a twofold nitrification occurs, the first through cyanogen compounds, and the second through ammonium compounds present in the heating gases. Hence, in the manufacture of steel with a high carbon content, it is highly desirable to purify the coal gas from the producers. The frequent tendency to brittleness and cracking in hardened steel is in many instances the result of an excessive proportion of nitrogen, although it is true that cracks may be formed, during the hardening of steel, as the consequence of unequal stresses in the outer layer of the



metal. In general, hardened steel is more sensitive to nitrogen than unhardened. The absolute influence of nitrogen on the mechanical properties of iron and steel is more injurious than that of phosphorus.

Since commercial iron invariably contains carbon, and since the chemical affinity of carbon for oxygen is greater, at high temperatures, than for any other substance, the nitrogen in iron and steel cannot occur in combination with oxygen, and therefore the only two possible compounds are iron nitride and iron cyanide.

The appearance of iron or steel is not always a reliable criterion of the proportion of nitrogen present. Although ordinary steel that is low in nitrogen has a bluish-grey colour, whilst steel that is rich in nitrogen is silver-white, these colours are sometimes reversed, the steel with a small percentage of nitrogen being silver-white, and that high in nitrogen bluish-grey. Analysis alone can afford reliable data for judging, since, speaking generally, there are no characteristic external indications that reveal the nitrogen content accurately.

Unfortunately too little attention is still paid to the importance of the nitrogen content. In specifications for girders, rails, &c., nitrogen is completely ignored; no definite limits are laid down, and the proportion may be high or low. It may be hoped that the time is not distant when the proportion of nitrogen will be expressly limited to a certain maximum. Nitrogen is particularly injurious to special steels; and all high grade steels must be kept free from this element if they are to fulfil the high requirements expected of them.

Phosphorus and sulphur have long been recognised as injurious ingredients of steel; but the action of nitrogen and oxygen is still more harmful, even when they are present only in very small quantities. We know that crucible steel contains very little nitrogen, a circumstance that explains its superiority to open-hearth steel, though their content of carbon, manganese, silicon, phosphorus, and sulphur may be identical. Numerous experiments carried out by the author have shown that vanadium combines with nitrogen and oxygen at high temperatures, thus freeing the charge from these injurious gases, and consequently an addition of vanadium affords the

best means of eliminating nitrogen. Since the same result is obtained with regard to oxygen, the addition of vanadium is extremely beneficial. At present, manganese and aluminium are largely used as deoxidisers in practice, but these are in no way capable of replacing vanadium.

It is well known that the separation of graphite is effected by the elements which pass into solution in iron, namely, silicon, nickel, &c.; whereas manganese, chromium, &c., which form double carbides with the cementite, prevent the deposition of graphite in high-carbon iron in presence of an increased addition of nickel and manganese. In all alloys of other metals with iron, the influence of these metals on the iron is in indirect ratio to their transformation point. The transformation point of nickel, for instance, is  $360^{\circ}$ , and that of manganese, minus  $180^{\circ}$ .

## II. THE CASE-HARDENING OF SPECIAL STEELS.

At the present time, special steels have almost entirely displaced all ordinary cement steels, owing to their durability and ease of case-hardening. At first, nickel steels containing 2 per cent. of nickel were used exclusively; but these did not fulfil expectations, being found deficient in hardness, tensile strength, and in surface hardness when tempered. This defect was remedied by adding 1.2 to 2.5 per cent. of chromium, in addition to the nickel. On the other hand, steel containing 6 to 7 per cent. of nickel does not require any further hardening after case-hardening, because, after hardening, its surface would assume the peculiar martensitic structure of tempered steel. In motor car construction, steel containing an increased percentage of carbon is now generally used, in order to increase the tensile strength and hardness of the metal, without taking into account the accompanying brittleness. Although theoretical investigations reveal great danger in compositions with a martensitic microstructure, use is made in practice of these compositions, which may easily become a source of danger under wrong thermal treatment or even when cooled to a few degrees below the ordinary temperature.

The reason for increasing the carbon content is to reduce the cost price, the danger being risked, in spite of all theoretical conclusions and warnings, and insufficient attention being paid to the brittleness accompanying the increased tensile strength of the metal. All parts that are to be hardened and tempered should be made of steel with a low content of carbon and nickel; whilst chromium steel should be used for bearings, silicon steel for springs and gear, and chromium-vanadium steel for all parts that will be subjected to considerable vibration, and at the same time are required to be hard.

### III. HARDENING MEDIA. ANNEALING AND HARDENING.

Improper and careless treatment of steel in hardening by cementation is usually followed by imperfect results, these being specially noticeable in the case of special steels. Every steel, whether with or without extraneous additions (nickel, chromium, tungsten, &c.), should always be treated carefully, in accordance with its properties and intended use. The furnace for case-hardening should be constructed so that a uniform temperature of  $1200^{\circ}$  C. can be maintained therein for a considerable time. Neither the fuel (coal) nor the flame should come into direct contact with the crucible—that is to say, the flame must lave the walls of the heating chamber uniformly, in order that the crucible may be heated solely by radiation, and not by direct heat. A furnace constructed on this plan will be found very reliable, and also economical in point of fuel consumption. The doors, chambers, and flues must be of best firebrick, the doors being made to fit tightly, and provided with closable viewholes about 8 inches in diameter. The temperature being ascertained by ocular inspection, these viewholes form a highly important detail, since they obviate the necessity for opening the doors unduly.

Fig. 1 represents a furnace for the case-hardening process that behaved admirably in the experiments described later. The upper chamber is intended for warming up the steel

to be case-hardened. The crucibles are made of wrought iron, and lined with about  $\frac{2}{5}$  inch of graphite. Though cast-iron crucibles are cheaper, preference is given to wrought iron, because the latter stands repeated heating far better than cast iron. The test-bars had a diameter of exactly 15 millimetres, and were exactly 150 millimetres long. The

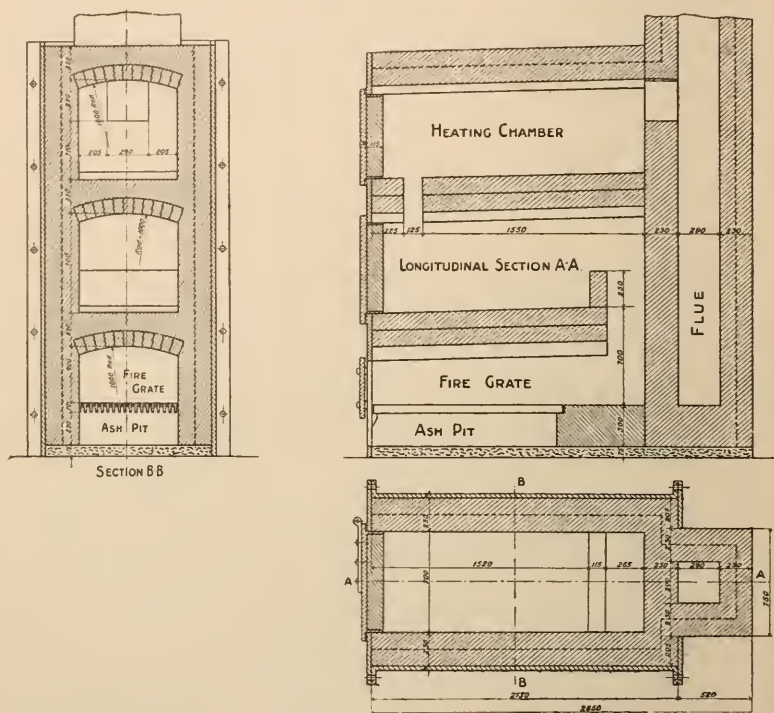


FIG. 1.

weight of each bar was determined as accurately as possible, both before and after the case-hardening, the thickness of the superficial layer being ascertained by the difference in weight at the end of the treatment.

The crucibles measured  $17\frac{1}{2} \times 12 \times 10$  inches, and were luted with good alumina, free from grease. They were charged by placing a  $1\frac{1}{2}$ -inch layer of the cementing medium at the

bottom of the crucible, the mass being compressed and then covered with the test-bars. The bars were placed about  $1\frac{1}{2}$  inch apart, so as not to come in contact with each other, or with the graphite lining of the crucible. Over the bars was spread a second  $1\frac{1}{2}$ -inch layer of the cementing powder, this being compressed as before. In this way the crucible was filled nearly up to the top, and finally covered with 2 inches of cementing powder. The chief aim kept in view in charging the crucible was to pack the contents as tightly as possible, in order to bring the carbon-carrying material into intimate contact with the bars.

After the carburising period, the crucible was taken out of the furnace and set in a dry place, out of the draught, to allow it to cool down uniformly. When the crucible has been carefully packed and luted, as described above, the colour of the finished bars should be white, or at most only slightly tinged with dark blue; the redder the appearance of the outer surface, the less careful and effective the filling and packing of the contents. This phenomenon is observable only when well carbonised, dry, and very finely ground leather, or pine bark, has been used. A good and cheap cementing medium is composed of sixty parts of ivory black (Eborustum), thirty-five parts of leather-charcoal powder (free from extraneous admixtures), three parts of potassium ferrocyanide ( $\text{Fe}(\text{Cy})_6\text{K}_4 + 3\text{H}_2\text{O}$ ), and two parts of copper sulphate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ), or saltpetre ( $\text{KNO}_3$ ). Carbon and barium carbonate in the proportion  $3\cdot2:1$  ( $80\text{C} + 25\text{BaCO}_3$ );  $1\cdot7:1$  ( $59\cdot5\text{C} + 35\text{BaCO}_3$ ); or  $1:1\cdot7$  ( $35\text{C} + 59\cdot5\text{BaCO}_3$ ), also furnish an extremely good cementing powder. Cyanides, too, have a carburising action at high temperatures, but with these media the crucible must not be filled too full. The following tables give the case-hardening capacity of various special steels when treated with the above carburising agents, which, for the sake of simplicity, have been marked as under:—

- A. Finely powdered leather charcoal.
- B. Finely powdered and well carbonised pine bark.
- C. 60 parts of ivory black, 35 parts of powdered leather charcoal, 3 parts of potassium ferrocyanide, and 2 parts of copper sulphate.
- D.  $80\text{C} + 25\text{BaCO}_3$ .
- E.  $59\cdot5\text{C} + 35\text{BaCO}_3$ .
- F.  $35\text{C} + 59\cdot5\text{BaCO}_3$ .



Cementing Medium.		Length of Experiment.	Temperature.	Thickness of Carburised Layer.
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TABLE I.— <i>Nickel Steels, 4 per cent. Ni.</i>				
		Hours.	Degrees C.	Millimetres.
A . . .		1	850	0·523
B . . .		2	900	0·678
C . . .		4	950	0·601
D . . .		6	1000	0·621
E . . .		8	1050	0·683
F . . .		10	1100	0·690

TABLE II.— <i>Nickel Steels, 6 per cent. Ni.</i>				
A . . .		1	850	0·543
B . . .		2	900	0·576
C . . .		4	950	0·621
D . . .		6	1000	0·631
E . . .		8	1050	0·658
F . . .		10	1100	0·701

TABLE III.— <i>Titanium Steels, 1·5 per cent. Ti.</i>				
A . . .		1	850	0·874
B . . .		2	900	0·883
C . . .		4	950	0·901
D . . .		6	1000	0·982
E . . .		8	1050	0·988
F . . .		10	1100	0·991

TABLE IV.— <i>Titanium Steels, 2·5 per cent. Ti.</i>				
A . . .		1	850	0·772
B . . .		2	900	0·778
C . . .		4	950	0·801
D . . .		6	1000	0·823
E . . .		8	1050	0·856
F . . .		10	1100	0·881

TABLE V.— <i>Silicon Steels, 0·4 per cent. Si.</i>				
A . . .		1	850	0·682
B . . .		2	900	0·691
C . . .		4	950	0·701
D . . .		6	1000	0·723
E . . .		8	1050	0·732
F . . .		10	1100	0·742

TABLE VI.— <i>Silicon Steels, 2·5 per cent. Si.</i>				
A . . .		1	850	0·362
B . . .		2	900	0·371
C . . .		4	950	0·391
D . . .		6	1000	0·401
E . . .		8	1050	0·408
F . . .		10	1100	0·412

Cementing Medium.	Length of Experiment.	Temperature.	Thickness of Carburised Layer.
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TABLE VII.—*Manganese Steels, 0·5 per cent. Mn.*

	Hours.	Degrees C.	Millimetres.
A . . .	1	850	0·982
B . . .	2	900	0·998
C . . .	4	950	1·024
D . . .	6	1000	1·087
E . . .	8	1050	1·112
F . . .	10	1100	1·213

TABLE VIII.—*Manganese Steels, 1·0 per cent. Mn.*

A . . .	1	850	1·201
B . . .	2	900	1·208
C . . .	4	950	1·301
D . . .	6	1000	1·308
E . . .	8	1050	1·312
F . . .	10	1100	1·321

TABLE IX.—*Manganese Steels, 1·5 per cent. Mn.*

A . . .	1	850	1·223
B . . .	2	900	1·228
C . . .	4	950	1·308
D . . .	6	1000	1·318
E . . .	8	1050	1·329
F . . .	10	1100	1·331

TABLE X.—*Manganese Steels, 2·0 per cent. Mn.*

A . . .	1	850	1·321
B . . .	2	900	1·338
C . . .	4	950	1·341
D . . .	6	1000	1·349
E . . .	8	1050	1·350
F . . .	10	1100	1·358

TABLE XI.—*Chromium Steels, 1·5 per cent. Cr.*

A . . .	1	850	1·012
B . . .	2	900	1·084
C . . .	4	950	1·116
D . . .	6	1000	1·148
E . . .	8	1050	1·151
F . . .	10	1100	1·199

TABLE XII.—*Chromium Steels, 2·0 per cent. Cr.*

A . . .	1	850	1·103
B . . .	2	900	1·108
C . . .	4	950	1·112
D . . .	6	1000	1·128
E . . .	8	1050	1·181
F . . .	10	1100	1·210

Cementing Medium.	Length of Experiment.	Temperature.	Thickness of Carburised Layer.
TABLE XIII.— <i>Chromium Steels, 2·5 per cent. Cr.</i>			
	Hours.	Degrees C.	Millimetres.
A . . .	1	850	1·210
B . . .	2	900	1·241
C . . .	4	950	1·263
D . . .	6	1000	1·283
E . . .	8	1050	1·301
F . . .	10	1100	1·308
TABLE XIV.— <i>Chromium Steels, 3·0 per cent. Cr.</i>			
A . . .	1	850	1·202
B . . .	2	900	1·253
C . . .	4	950	1·283
D . . .	6	1000	1·301
E . . .	8	1050	1·312
F . . .	10	1100	1·321
TABLE XV.— <i>Tungsten Steels, 0·4 per cent. W.</i>			
A . . .	1	850	0·803
B . . .	2	900	0·808
C . . .	4	950	0·902
D . . .	6	1000	0·912
E . . .	8	1050	0·943
F . . .	10	1100	0·957
TABLE XVI.— <i>Tungsten Steels, 1·0 per cent. W.</i>			
A . . .	1	850	0·921
B . . .	2	900	0·938
C . . .	4	950	0·946
D . . .	6	1000	0·956
E . . .	8	1050	0·981
F . . .	10	1100	0·991
TABLE XVII.— <i>Tungsten Steels, 2·0 per cent. W.</i>			
A . . .	1	850	1·014
B . . .	2	900	1·036
C . . .	4	950	1·045
D . . .	6	1000	1·058
E . . .	8	1050	1·081
F . . .	10	1100	1·091
TABLE XVIII.— <i>Tungsten Steels, 2·5 per cent. W.</i>			
A . . .	1	850	1·231
B . . .	2	900	1·262
C . . .	4	950	1·283
D . . .	6	1000	1·296
E . . .	8	1050	1·298
F . . .	10	1100	1·301



Cementing Medium.	Length of Experiment.	Temperature.	Thickness of Carburised Layer.
TABLE XIX.— <i>Molybdenum Steels, 0.5 per cent. Mo.</i>			
	Hours.	Degrees C.	Millimetres.
A . . .	1	850	0.734
B . . .	2	900	0.786
C . . .	4	950	0.791
D . . .	6	1000	0.843
E . . .	8	1050	0.878
F . . .	10	1100	0.971
TABLE XX.— <i>Molybdenum Steels, 1.0 per cent. Mo.</i>			
A . . .	1	850	0.901
B . . .	2	900	0.923
C . . .	4	950	0.932
D . . .	6	1000	0.946
E . . .	8	1050	0.958
F . . .	10	1100	0.968
TABLE XXI.— <i>Molybdenum Steels, 2.0 per cent. Mo.</i>			
A . . .	1	850	1.124
B . . .	2	900	1.163
C . . .	4	950	1.184
D . . .	6	1000	1.193
E . . .	8	1050	1.201
F . . .	10	1100	1.208
TABLE XXII.— <i>Molybdenum Steels, 3.0 per cent. Mo.</i>			
A . . .	1	850	1.283
B . . .	2	900	1.297
C . . .	4	950	1.301
D . . .	6	1000	1.323
E . . .	8	1050	1.384
F . . .	10	1100	1.396

With these six different cementing media, acting under equal conditions of time and temperature, the thickness of the carburised layer, in the case of an ordinary carbon steel, averaged 0.891 millimetre. As was shown by these experiments, the tensile properties of a steel low in carbon are increased by even a small percentage of nickel, without any appreciable loss of toughness being recorded. The addition of nickel enables the iron to take a high polish. With a high nickel content, rapid cooling quickly reduces the point of transformation from martensite to pearlite in the core. The author came to the conclusion that a troostitic structure is temporarily produced during this transformation. Hence,

owing to the increasing carbon content, the increase of hardening is augmented by case-hardening, this increase causing high stresses—revealed by cracks—in the metal when cooled suddenly. For this reason, and also because the structure is already martensitic, rapid cooling of nickel steel is injurious, and not to be recommended. In manganese steels, too, the transformation of martensite into pearlite proceeds by the intermediate formation of troostite under sudden cooling. Both the nickel steels and manganese steels examined contained martensite in the outermost carburised layer. With regard to the tungsten-chromium-titanium steels examined, it may be said that their mechanical properties do not gain any important improvement by case-hardening, so that this treatment may well be omitted in practice. Silicon steels are not improved by case-hardening, their low forging capacity and toughness remaining unchanged. The absorption of carbon by silicon steels during case-hardening depends on the silicon content; when this is exactly 6.79 per cent., no absorption of carbon occurs, and the whole of the carbon is graphitic.

For the successful annealing or hardening of a steel tool, a uniform heating to a temperature slightly above the transformation point ( $Ac_1$ ) is necessary, followed by slow cooling (for annealing), or sudden cooling in water (for hardening), before the temperature has fallen to  $Ar_1$ . Hardening in oil proved satisfactory in all cases where it was desired to impart high ductility, at the same time, to steel low in carbon. Since the introduction of pyrometry, the judging of temperatures by the eye is less frequently practised, though, with a little experience, a fairly accurate idea of the temperature can be obtained by the unassisted eye. Temperature indicators (metals, earthy silicates, or alloys) depend greatly on their fusibility; and the metals and alloys suffer from the defect of being readily oxidised. The earthy silicates—to which category belong the Seger cones—have, in common with all the different kinds of fireproof materials, behaved very well at temperatures from  $700^{\circ}$  to  $800^{\circ}$  C.; though they have the same defects as other indicators which gradually soften without melting. Temperature indicators con-

sisting of metallic salts have such readily observable and accurately determinable solidification-points that they may, with justice, be classed along with the most sensitive instruments of precision, the melting-point of barium chloride, for instance, being  $930^{\circ}$  C., and that of potassium chloride  $740^{\circ}$  C., with a slight margin of deviation amounting to  $2^{\circ}$  to  $3^{\circ}$  C. This margin is entirely negligible in practice, no injurious influences being set up at differences less than  $8^{\circ}$  to  $10^{\circ}$  C. Brayshaw, however, avers that a variation of  $1^{\circ}$  C. in the hardening temperature is injurious, and that one of  $5^{\circ}$  C. makes all the difference between good and bad hardening.

Most of the failures, however, are generally due to the steel being overheated, whereby the grain of the metal is usually rendered coarse, although the original fineness of structure can be restored by reheating to a suitable temperature. In this connection, the author examined a hard open-hearth steel of the following composition: carbon, 1.28 per cent.; manganese, 0.232 per cent.; sulphur, 0.002 per cent.; phosphorus, 0.029 per cent., and silicon, 0.031 per cent.; and arrived at the conclusion that the change occurring above  $Ac_1$  was due, not to the duration of the heating process, but solely to the height of the temperature, since a sample that had been kept for two hours at  $790^{\circ}$  C. exhibited greater changes in the same time than another which had been cooled from a temperature of  $785^{\circ}$  C.

If  $Ac_1$  be exceeded in heating, the pearlite is suddenly transformed into martensite, leaving the free cementite unaltered. If the temperature of an iron bar be raised above  $Ac_1$ , the solubility of the carbon increases in the same degree, the result being that the free cementite is divided, and the martensite becomes richer in carbon. The higher the rise in temperature, the greater the progress of division of the cementite, up to the moment when the point  $A_3$  is reached, at which the solvent capacity of  $\gamma$ -iron corresponds to the carbon content of the steel, and all the cementite becomes converted into martensite. On the decomposition of the cementite, its carbon is distributed uniformly through the metal. The cementite is separated as soon as the steel is

cooled, the solvent capacity of the  $\gamma$ -iron being thereby greatly reduced.

This separation of the cementite does not present the old structure formerly exhibited by the coarse grain, but a finer-grained structure. The fineness or coarseness of the network is determined by the dimensions of the grains of martensite, since the cementite is deposited between them in the process of separation. The formation of grain depends on the grouping of the small crystalline molecules around certain poles; and this polarisation occurs the more readily as the temperature is higher, the grains being then correspondingly larger.

The noteworthy fact, that cementite gives a finer structure after reheating than before, is attributable to the destruction of the powerful polarisation by overheating, and to the prevention of its recurrence during an equally complete reheating. The polarisation can be destroyed if the steel exceeds  $A_c$ , on reheating, and the pearlite is transformed into martensite. Although this view was shared by Brinell and K. F. Goransson\* it does not seem to the author to be correct, for polarisation may also have been destroyed during the cooling down below  $A_r$  after the superheating, presuming the polarisation to have occurred in martensite. This presumption is not improbable, since it may well be assumed that the polarisation is more readily destroyed during the transition from martensite to another structure than under the reverse conditions of a transformation of some other structure into martensite. Moreover, if one bears in mind that the carbon is chemically combined by the transformation of martensite into pearlite, and that the latter arranges itself as a settled mass, one is justified in assuming that some connection exists between the presence of grains and critical temperatures, and that in order to make superheated steel fine-grained without working it, the metal must be raised to the temperature  $A_3$  at which the solvent power of the  $\gamma$ -iron corresponds to the carbon content of the steel.

It may also be regarded as probable that this applies equally to steel that is low in carbon, *i.e.* steel in which

\* *Jernkontorets Annaler*, 1902, Part III.

ferrite takes the place of free cementite, since the experiments of Stead point in that direction. Stead found that with 0.01 per cent. of carbon the grain became finer at 900° C., and at 870° C. with 0.11 per cent. of carbon. These temperatures are those at which the solvent power of martensite toward ferrite corresponds to the said percentages of carbon.

#### IV. METALLOGRAPHICAL, MICROSCOPICAL, AND MICROGRAPHICAL EXAMINATION OF VARIOUS SPECIAL STEELS. MECHANICAL AND PHYSICAL PROPERTIES.

##### A. NICKEL-CHROMIUM STEEL.

In the following Table I. the steels of the first two series contain 0.3 per cent. and 0.9 per cent. of carbon respectively. By the addition of 4 per cent., 8 per cent., and 19 per cent. of chromium they were transformed (*a*) into a pearlitic steel with about 6 per cent. of nickel, (*b*) martensite steel with about 11 per cent. of nickel, and (*c*)  $\gamma$ -iron steel with about 25 per cent. of nickel.

The third series consists of steels with 4 per cent. of carbon, 3 per cent. of nickel, and 0.6 per cent. to 4 per cent. of chromium. The fourth series demonstrates the influence of chromium on the structure of such steels as exhibit a structure between pearlite and martensite. Steels Nos. 3 to 6 and No. 12 with 19 per cent. of carbon (Series I.) cannot be forged, although that treatment is possible with No. 1 and No. 10. In Series II. only the steels Nos. 13, 14, 15, and 16 are forgeable.

The investigations detailed below relate both to the normal steels and to those that were suddenly cooled, reannealed, and subjected to the influence of high temperatures.

The metallographical examination of the normal steels showed that not a single member of the first series exhibited pearlitic structure. Steel No. 1, after a short etching with picric acid, showed very fine martensite, with traces of ferrite. Steel No. 2 revealed a coarser martensite, accompanied by a very small amount of troostite-sorbite. Steel No. 3 showed



TABLE I.

## Series I.

No.	Kind.	C.	Ni.	Cr.	Si.	S.	P.	Mn.
		Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
1	3Ni6, Cr4	0.167	5.56	3.55	0.180	0.007	0.011	0.176
2	3Ni6, Cr8	0.253	5.70	7.86	0.273	0.021	0.014	0.148
3	3Ni5, Cr19	0.167	6.30	19.12	0.444	0.007	0.008	0.012*
4	3Ni11, Cr4	0.305	12.78	3.91	0.625	0.041	0.041	traces
5	3Ni11, Cr8	0.301	11.12	8.25	0.737	0.031	0.003	traces
6	3Ni11, Cr19	0.220	20.34	19.71	0.219	0.010	0.010	traces*
7	3Ni6, Cr4	0.170	19.68	3.07	0.391	0.012	0.002	0.251
8	3Ni5, Cr8	0.210	24.21	15.01	0.482	0.026	0.016	0.189
9	3Ni6, Cr19	0.216	25.32	15.18	0.873	0.013	0.018	0.176
10	3Ni25, Cr4	0.280	30.46	20.12	0.754	0.042	0.002	0.054
11	3Ni25, Cr8	0.181	32.68	19.76	0.635	0.056	0.005	traces
12	3Ni25, Cr19	0.142	30.79	29.38	0.521	0.010	0.010	traces*
Series II.								
13	9Ni6, Cr4	0.896	6.53	4.41	0.545	0.017	0.017	0.324
14	9Ni6, Cr8	1.052	5.64	7.52	0.211	0.012	0.013	0.022
15	9Ni6, Cr19	0.981	5.31	19.61	0.321	0.024	0.026	0.308
16	9Ni11, Cr4	0.963	11.21	4.13	0.517	0.023	0.012	0.412
17	9Ni11, Cr8	0.923	11.01	8.27	traces	0.021	0.028	traces*
18	9Ni11, Cr19	0.826	26.13	19.31	traces	0.016	0.017	traces
19	9Ni6, Cr4	0.786	25.27	3.91	0.327	0.012	0.021	0.412
20	9Ni6, Cr8	0.864	25.01	8.97	0.512	0.021	0.005	0.168
21	9Ni6, Cr19	0.542	27.37	19.21	0.431	0.017	0.080	0.307
22	9Ni25, Cr4	0.831	31.01	4.01	0.331	0.016	0.012	0.562
23	9Ni25, Cr8	0.764	29.41	8.01	0.276	0.011	0.005	0.066
24	9Ni25, Cr19	0.910	29.13	19.76	0.187	0.012	0.013	0.078
Series III.								
25	4Ni3, Cr0.6	0.345	2.31	0.52	0.232	0.016	0.027	0.731
26	4Ni3, Cr0.5	0.195	2.14	0.90	0.275	0.009	0.019	0.243
27	4Ni3, Cr1.0	0.221	2.56	1.98	0.167	0.004	0.015	0.189
28	4Ni3, Cr2.0	0.286	2.22	4.27	0.172	0.022	0.021	0.315
29	4Ni3, Cr3.0	0.295	2.75	3.36	0.125	0.019	0.016	0.210
30	4Ni3, Cr4.0	0.364	2.50	5.28	0.237	0.017	0.028	0.136
Series IV.								
31	3Ni7, Cr0.5	0.170	6.78	0.25	0.082	0.004	0.017	0.078
32	3Ni7, Cr1.0	0.141	6.28	1.20	0.127	0.005	0.032	0.092
33	3Ni7, Cr1.0	0.295	7.30	0.92	0.045	0.005	0.021	0.103
34	3Ni7, Cr1.0	0.210	6.02	0.81	0.078	0.006	0.020	0.119
35	3Ni7, Cr2.0	0.240	7.90	1.81	0.108	traces	0.021	0.178
36	3Ni7, Cr5.0	0.190	7.36	4.98	0.119	0.005	0.023	0.189
37	3Ni7, Cr6.0	0.175	6.07	5.79	0.175	0.006	0.022	0.063

\* Not forgeable.

round carbide granules without etching; and strong etching with hydrochloric acid revealed pure  $\gamma$ -iron in the background. Steel No. 4 had a martensitic appearance. Steel No. 5 showed martensite with extremely fine granules of ferrite. Steel No. 6 possessed large carbide granules with  $\gamma$ -iron in the foreground. Steel No. 7 contained decided polyhedra with little carbide and  $\gamma$ -iron. Steel No. 8 showed  $\gamma$ -iron with less sharply defined polyhedra and no trace of carbide. Steel No. 9 was chiefly composed of martensite and ferrite. Steels Nos. 10 and 11 were formed of  $\gamma$ -iron and carbide. Steel No. 12 showed very small quantities of carbide,  $\gamma$ -iron predominating.

*Series I.*—The following points are specially worthy of note: Steel No. 1 is martensitic; a steel of the same composition, but without nickel or chromium, would show slight traces of pearlite. It follows, therefore, that both these metals act in the same way. Strangely enough, not a single steel of this series contains martensite and carbon together, although both chromium-free and nickel-free steel would be martensitic; in this case the action of these metals is not identical but opposite. Steels Nos. 10, 11, and 12 show that chromium favours the tendency of nickel to form  $\gamma$ -iron. Steel No. 12 also contains far less carbide than would have been the case in a corresponding nickel-free steel.

*Series II.*—Steel No. 13 contains small rounded polyhedra with very fine martensite grains, exhibiting needles of troostorsorbite at the edges; this phenomenon is due to insufficient decarburisation. Steel No. 14, when etched with hydrochloric acid, reveals well-formed polyhedra with very fine martensite. The structure of steel No. 15 is analogous to that of No. 3 of Series I.; from which it follows that a higher carbon content accelerates the formation of carbide. Steel No. 16 contains  $\gamma$ -iron and carbide granules, forming a fairly decided eutectoid. Steels Nos. 17 and 18 show the same structure as No. 14, except that here the martensite appears coarser. Steels Nos. 19 and 20 are composed of  $\gamma$ -iron and traces of carbide. Steels Nos. 21, 22, 23, and 24 are  $\gamma$ -iron steels, with the lines of demarcation of the very small, rounded polyhedra considerably broader than in ordinary  $\gamma$ -iron steels.

In this series, also, pearlite is lacking, on account of the high content of nickel and chromium. It is also evident that the carbide content increases with the percentage of chromium.

*Series III.*—This series shows the transition of pearlitic structure into martensitic. Steel No. 25 shows pearlite and fine granules of ferrite. Steels Nos. 26, 27, and 28 reveal the transition from pearlite to martensite in a very decided manner, the martensitic structure being predominant and the pearlite almost entirely suppressed. Steels Nos. 29 and 30 are perfectly martensitic.

*Series IV.*—Since the action of chromium and nickel is similar, all the steels of this series (Nos. 33, 34, 35, 36, and 37) are martensitic. Steels Nos. 31 and 32 exhibit martensite and a little ferrite.

The results of these experiments show that in nickel-chromium steels the transition from the pearlitic structure to the martensitic is apparently influenced by and dependent on the total carbon + nickel + chromium, and that the effects of nickel and chromium may neutralise one another—probably owing to imperfect decarburisation. The formation of carbide, which is dependent on the carbon content of the steel, increases in martensitic steels with the chromium content, and requires the effect of nickel to form  $\gamma$ -iron. Chromium acts on  $\gamma$ -iron steels in the same manner. With a given chromium content, the amount of carbide separated depends on the percentage of carbon in the metal, though the carbide content is always smaller than in a corresponding nickel-free steel. In all the chromium-nickel steels with a high carbon content and carbide, the black background does not show up after the picric acid etching in the same way as occurs with chromium steels.

(1) *Examination of the Mechanical Properties.*—Even the smallest amount of carbide is injurious to the working of chromium-nickel steels, to an even greater extent than in the case of nickel-free steels; for, in spite of the high chromium content, the steels Nos. 3, 4, 5, 6, and 12 of Series I. (Table I.) are not forgeable; and the same applies to the steels Nos. 22, 23, and 24 (Table I.) of Series II. with a high



nickel content. From this it is evident that the carbon content exerts a great influence on all chromium-nickel steels.

These tensile tests showed:—

1. That the steels which contain double carbide in addition to martensite exhibit a high elastic limit and breaking strength; but that both these limits are lowered considerably as the carbide content increases.

2. That in steels with pearlitic structure the action of chromium and nickel is cumulative, the tensile strength being increased, whilst the ductility is diminished.

3. That martensitic steels with high tensile strength have a low ductility. In pure martensite steel the elastic limit is near the breaking limit.

4. That  $\gamma$ -iron steels with carbide inclusions possess high elasticity and tensile strength; the ductility and reduction of section vary quite in accordance with the carbon content.

5. That the  $\gamma$ -iron steels possess high tensile strength, far exceeding that of the chromium-free steels.

(2) *Hardness and Impact Tests.*—These experiments gave the following results:—

1. The brittleness of the  $\gamma$ -iron steels containing carbide increases with the augmentation of the carbide content.

2. The carbide-free  $\gamma$ -iron steels are of medium hardness, and the degree of brittleness is exceedingly low.

3. The pearlitic steels are not brittle. Their hardness increases with the chromium content, and consequently also their resistance to impact.

4. All martensitic steels are very brittle, owing to their great hardness.

(3) *Suddenly Cooled Steels.*—All the steels were cooled suddenly at  $850^{\circ}$  C. The metallographic examination gave the following results:—

*Series I.*—1. In contrast to the fine martensite of normal steel, the martensite of the steel No. 1 in this case appeared coarser in grain.

2. Steel No. 2 remained unaltered.

3. Steel No. 4 exhibited areas of  $\gamma$ -iron in addition to martensite.

TABLE II.

Series I.

No.	Description.	Structure.	(a) NORMAL STEELS.				(b) QUENCHED STEELS.					
			Tensile Tests.			Shock.	Hardness.	M.	Tensile Tests.			Shock.
			Elongation.	Elastic Limit.	Tensile Strength.				Elongation.	Elastic Limit.	Tensile Strength.	
			Per Cent.	Lbs. per Sq. In.					Per Cent.	Lbs. per Sq. In.		
1	3Ni6, Cr4	Martensite and ferrite.	12.0	121,086	157,162	9	271	51.0	9.0	184,185	214,764	4
2	3Ni6, Cr8	Martensite and troostite and sorbite.	6.0	106,671	186,745	9	481	46.3	7.0	208,144	268,144	8
4	3Ni11, Cr4	Martensite.	5.0	214,764	248,210	9	467	38.0	19.0	100,982	132,272	9
5	3Ni11, Cr8	Martensite-ferrite.	11.0	128,147	142,940	12	191	23.0	...	Broken	...	9
7	3Ni6, Cr4	γ-Iron carbide.	19.0	113,782	137,961	12	237	69.0	14.0	72,962	129,428	13
8	3Ni6, Cr8	γ-Iron.	28.0	78,225	106,671	31	129	62.0	30.0	70,402	103,827	39
9	Ni6, Cr19	Martensite and ferrite.	10.0	129,142	160,006	12	281	29.0	10.0	274,500	274,500	6
10	3Ni25, Cr4	γ-Iron carbide.	20.0	120,894	140,095	12	243	19.0	20.0	89,603	140,866	29
11	3Ni25, Cr8	γ-Iron carbide.	21.0	96,715	144,361	7	240	61.0	15.0	83,914	133,695	29

Series II.															
13	9Ni6, Cr4	Martensite with little troostite-sorbite.	0.0	142,228	168,540	48.0	367	5	Martensite.	24.0	129,854	192,001	18.0	411	6
14	9Ni6, Cr8	Martensite.	1.8	230,410	237,520	0.0	281	6	Martensite.	28.0	107,382	209,075	21.0	522	1
15	9Ni6, Cr19	γ-iron with little carbide.	35.0	72,536	123,739	71.0	297	29	γ-iron and carbide.	30.0	86,753	140,866	59.0	199	19
16	9Ni11, Cr4	γ-iron with little carbide.	30.5	58,313	135,117	78.0	301	27	γ-iron and carbide.	37.0	75,380	143,650	66.0	196	25
Series III.															
25	4Ni3, Cr0.6	Pearlite and ferrite.	31.0	95,293	92,448	23.0	171	31	Martensite and pearlite.	2.0	169,251	184,467	0.0	420	1
26	4Ni3, Cr0.5	Martensite and traces of pearlite.	18.0	72,536	100,982	25.0	165	27	Martensite.	2.0	179,207	196,986	0.0	435	4
27	4Ni3, Cr1.0	Martensite and traces of pearlite.	20.0	69,692	103,827	22.0	159	7	Martensite.	3.0	197,697	238,658	0.0	451	2
28	4Ni3, Cr2.0	Martensite and traces of pearlite.	21.0	76,803	108,804	26.0	171	7	Martensite.	3.0	253,166	272,082	0.0	463	3
29	4Ni3, Cr3.0	Martensite.	1.5	200,501	224,720	31.0	250	7	Martensite.	3.5	254,588	276,634	0.0	463	5
30	4Ni3, Cr4.0	Martensite.	2.5	211,010	243,210	28.5	258	7	Martensite.	3.5	201,252	283,887	0.0	471	6
Series IV.															
31	3Ni7, Cr0.5	Martensite and ferrite.	21.0	68,080	115,205	27.6	194	23	Martensite.	8.8	200,541	224,720	10.5	281	9
32	3Ni7, Cr1.0	Martensite and ferrite.	17.0	57,602	127,294	28.5	180	28	Martensite.	7.6	283,034	246,054	12.3	395	7
33	3Ni7, Cr1.0	Martensite.	10.0	153,606	176,363	51.3	288	19	Martensite.	0.0	214,761	211,919	0.0	481	22
34	3Ni7, Cr1.0	Martensite.	9.0	158,584	183,474	48.2	291	10	Martensite.	0.0	183,474	200,541	8.5	430	22
35	3Ni7, Cr2.0	Martensite.	7.0	182,763	228,987	29.3	404	8	Martensite.	0.0	256,054	260,277	4.3	395	4
36	3Ni7, Cr5.0	Martensite.	6.0	194,141	244,632	31.8	446	7	Martensite.	0.0	257,433	257,433	1.5	410	1
37	3Ni7, Cr6.0	Martensite.	7.0	200,541	159,295	49.7	451	6	Martensite.	0.0	261,944	261,944	18.6	437	1

4. Steels Nos. 5, 7, 8, 9, 10, and 11 remained unaltered.

*Series II.*—1. Steel No. 13 had lost its troosto-sorbite, a circumstance that must be regarded as a consequence of insufficient decarburisation.

2. Steels Nos. 14 and 15 had not changed their structure. Steel No. 16 alone suffered a slight diminution of  $\gamma$ -iron.

*Series III.*—1. Steel No. 25 had entirely lost its ferrite, insignificant traces of pearlite appearing in the foreground with martensite.

2. The traces of pearlite in steel No. 26 were no longer discernible, whereas martensite predominated in large aggregations.

3. Steels Nos. 27, 28, 29, and 30 were martensitic.

*Series IV.*—All the steels had retained their martensitic structure and exhibited a trace of  $\gamma$ -iron.

(4) *Case-hardened Steels.*—These steels were subjected to heating for three days at  $1150^{\circ}$  C., in a mixture of finely carbonised leather with pine bark (3:1). Under this treatment all the martensitic steels—without reference to carbide content—exhibited very large carbide granules at the edges, and also small traces of troosto-sorbite needles, the number increasing toward the interior.  $\gamma$ -iron increased in direct ratio to the carbon content of the stratum. Case-hardened  $\gamma$ -iron steels exhibited large polyhedra, bounded by exceedingly fine and uniform carbide (in contrast to the martensitic steels). The carbide steels contained large quantities of carbide, especially at the marginal zones. The pearlitic steels exhibited a twofold appearance, large quantities of cementite needles being discernible in the marginal zones in some instances, whilst in others the amount of pearlite in the marginal zone was very small, and the cementite needles were very sharply defined.

(5) *Conclusions.*—The foregoing results indicate that the following structure may occur in normal bars:—

- |                             |                                    |
|-----------------------------|------------------------------------|
| 1. Pearlite and ferrite.    | 5. Martensite with $\gamma$ -iron. |
| 2. Pearlite and carbide.    | 6. Martensite with ferrite.        |
| 3. Martensite with carbide. | 7. $\gamma$ -Iron with carbide.    |
| 4. Martensite.              | 8. $\gamma$ -Iron.                 |

If the total carbon plus nickel, and also the amount of chromium, be not large, the pearlitic steels retain their structure, only becoming martensitic in the case of a high chromium content and an increased content of carbon and nickel. The formation of martensite depends on the sum carbon + chromium + nickel. With the ratio 1.68 carbon, 18.3 chromium, 28.7 nickel, these three elements are equivalent. Carbide structure appears in  $\gamma$ -iron only when the chromium content is increased. If the percentage of chromium be low, the carbon content must be correspondingly higher in order to effect the formation of carbide. As a structural element, carbide is possible only with a very high content of chromium. The structure of martensitic steels with a low chromium content does not change. An increase of chromium leads to the formation of carbide; and if the increase be considerable, a texture of martensite ( $\gamma$ -iron and carbide) is obtained.

The mechanical properties of martensitic steels are high tensile strength, increased elastic limit, and low ductility. Martensitic steels with double carbide suffer a loss of tensile strength and elasticity as the carbide content increases.  $\gamma$ -iron steels possess a higher elastic limit and tensile strength than the corresponding chromium-free nickel steels, but the ductility and resistance to impact are considerably lower, the hardness remaining nearly the same. Steels with  $\gamma$ -iron and carbide have the same mechanical properties as the  $\gamma$ -iron steels, though their ductility is slightly lower and their brittleness greater. Hence it may be said that, in the case of chromium-nickel steels, the chromium alone produces a high tensile strength and high elastic limit. The influence of sudden cooling on quaternary pearlitic steel is very slight, but is much the more apparent in the case of ternary pearlitic steels. The martensitic steels exhibit a great tendency to the formation of  $\gamma$ -iron. They retain their structure, like the  $\gamma$ -iron steels, whereas the influence of sudden cooling on carbide steels is first apparent at temperatures above 1300° C.

Generally speaking, the processes of annealing and case-hardening are of no particular utility in connection with the



industrial application of these steels. The first-named only makes the steels softer, without producing any alteration of structure, whilst it is only in the case of pearlitic steels that the second treatment affords the slight advantage of rendering the superficial layer martensitic. From the foregoing experiments it is clearly evident that only chromium-nickel steels with pearlitic and  $\gamma$ -iron structure can be recommended for industrial and practical use.

### B. NICKEL STEEL.

The micrographical examination was extended to the following three series of steels:—

Series I. contained an average of 0.15 per cent. carbon and 2.5 to 3.5 per cent. nickel.

Series II. contained an average of 0.3 per cent. carbon and 2 to 2.8 per cent. nickel.

Series III. contained an average of 0.95 per cent. carbon and 2.1 to 2.9 per cent. nickel.

The highest amount of manganese in these steels was 0.131 per cent., the maximum silicon content was 0.10 per cent., and the highest sulphur content, 0.0073 per cent.

The experiments were performed on the specimens in an annealed, naturally-hard, hardened, and cold-worked condition. Annealing for six hours in an electrically heated furnace, at a temperature of 1000° C., had no appreciable influence on the samples consisting of  $\gamma$ -iron and pearlite, though a slight tendency to the formation of martensite seemed to be manifested. In other respects the influence of annealing was the same as with ordinary carbon steels. The other samples also sustained no more important alterations than such as generally appear during hardening. The naturally-hard samples contained the following structural constituents:—

Constituents.	Series I. Carbon, 0.15 per Cent.	Series II. Carbon, 0.3 per Cent.	Series III. Carbon, 0.95 per Cent.
$\gamma$ -iron with pearlite .	0 to 13	0 to 10	0 to 6.5
Pure martensite .	13 to 33	10 to 31	6.5 to 23
Pure $\gamma$ -iron .	over 33	over 31	over 23

It is evident that the alterations in the structure are influenced by the amount of nickel present and dependent on the carbon content of the steel. The only important changes of structure occur with very low percentages of nickel and high carbon content. Steels of pure martensite with high carbon content are very difficult to work, the difficulties increasing directly with the growing carbon content.

All the specimens consisting of pure  $\gamma$ -iron, with low nickel content, exhibited arrow-shaped crystals when hardened; but in those with a high content of nickel these crystals were discernible with difficulty. The specimens consisting of pure martensite showed  $\gamma$ -iron structure. Those composed of  $\gamma$ -iron and pearlite suffered the same alterations as occur in ordinary steel.

The results of the tensile tests of the naturally-hard steels can be seen from the following tables:—

*Steel with 0.15 per Cent. Carbon.*

Nickel Content.	Tensile Strength.	Elastic Limit.	Elongation.	Decrease in Section.
Per Cent.	Lbs. per Sq. In.	Lbs. per Sq. In.	Per Cent.	Per Cent.
2.5	55,042	45,939	26.0	81.4
5.0	74,812	64,857	12.0	30.2
10.0	99,701	85,763	10.0	59.2
15.0	144,076	114,351	0.9	2.1
20.0	175,794	153,028	17.0	6.2
25.0	186,978	139,097	21.0	4.3
30.0	146,641	99,985	9.0	5.1
35.0	71,540	59,167	35.5	71.8

*Steel with 0.3 per Cent. Carbon.*

Nickel Content.	Tensile Strength.	Elastic Limit.	Elongation.	Decrease in Section.
Per Cent.	Lbs. per Sq. In.	Lbs. per Sq. In.	Per Cent.	Per Cent.
2.5	60,162	58,456	24.0	71.3
5.0	163,704	127,578	8.0	28.7
10.0	178,211	128,574	4.6	37.6
15.0	146,210	98,563	9.1	41.3
20.0	142,086	137,108	11.6	9.7
25.0	198,834	130,565	6.7	4.3
30.0	122,742	78,651	32.1	32.5
35.0	115,774	68,980	38.3	78.6

*Steel with 0.95 per Cent. Carbon.*

Nickel Content.	Tensile Strength.	Elastic Limit.	Elongation.	Decrease in Section.
Per Cent.	Lbs. per Sq. In.	Lbs. per Sq. In.	Per Cent.	Per Cent.
2.5	130,565	68,695	22.0	65.2
5.0	165,990	142,754	8.7	22.3
10.0	168,255	102,120	9.1	31.6
15.0	134,264	126,725	12.3	38.4
20.0	130,423	128,431	19.1	11.4
25.0	187,314	141,801	7.8	3.9
30.0	125,730	89,319	38.6	29.8
35.0	112,786	87,470	39.1	62.7

Hence, steel with about 25 per cent. of nickel has the highest tensile strength and lowest toughness, whereas the specimens low in carbon attain their highest tensile strength with a low nickel content. Impact tests with nicked specimens of naturally-hard steel showed that the specimens with high nickel content (over 25 per cent. nickel) and medium carbon content exhibited the greatest strength. The specimens with 12 to 15 per cent. of nickel had very low powers of resistance. The maximum degree of hardness under the Brinell test was found in the specimens with high carbon content and low percentage of nickel.

An increased nickel content raises the tensile strength, but lessens the elongation. All iron-nickel alloys exhibit, to a greater or smaller extent, a characteristic brittle zone, the steels in which possess high tensile strength and low ductility. Tests with nickel steels with 3 to 35 per cent. of nickel and 0.28~0.87~0.94~0.98~1.0~1.12~1.21~1.28 and 1.3 carbon exhibit this peculiarity, as shown below. The brittle zone, that is to say the minimum ductility, was as follows :—

In steel with 0.28 per cent. carbon at 14.0 per cent. nickel

0.87	8.9	“	“
0.98	8.8	“	“
0.98	8.3	“	“
1.00	8.0	“	“
1.12	7.8	“	“
1.21	6.5	“	“
1.28	5.1	“	“
1.30	2.3	“	“

The mechanical tests were performed in various ways. The



bars examined had a diameter of 15 millimetres (0·59 inch) and a length of 150 millimetres (5·9 inch), and were heated to 850° C., followed by slow cooling, for about eighteen hours, in fine, dry sand. The behaviour of certain of these steels when forged is worthy of note, it being found that cast steels with a polyhedral structure, which underwent transformation into martensite on forging, resumed their original polyhedral structure. The carbon content of these steels varied between 0·11 per cent. and 0·87 per cent., and the nickel content between 10 per cent. and 15 per cent.

Iron-nickel alloys containing between 16 per cent. and 35 per cent. of nickel are extremely difficult to forge, and those with 24 to 35 per cent. of nickel cannot be forged at all. The acicular crystalline structure reduces their workability to a very low point. The tensile strength increases with the nickel content up to about 15 per cent. nickel, in the same proportion as the workability diminishes. The limit of proportionality attains its highest value in the presence of 8·5 per cent. nickel. Both in wrought and cast metal the rising nickel content has no special influence, and is about the same in each case. Certainly, there is one point of difference, inasmuch as the maximum value with regard to tensile strength and limit of stretch is reached with 16 per cent. of nickel in the case of mechanically treated specimens, as compared with 8 per cent. of nickel in the cast specimens. The tensile strength of the round bars containing 10 to 15 per cent. nickel was considerably increased by rolling. The presence of graphite in iron-nickel alloys containing carbon impairs the strength very considerably; and care must therefore be taken that, in solidifying, alloys free from graphite are obtained. Additions of manganese exceeding 0·7 per cent. manganese should never be made, since, with few exceptions, they reduce the tensile strength and ductility. Cast non-graphitic alloys with 0·4 to 0·7 per cent. manganese, in the presence of 16 per cent. nickel and 0·11 to 0·28 per cent. carbon, attain the highest tensile strength with low elongation. Converse properties are exhibited by non-graphitic alloys containing 0·38 to 0·65 per cent. manganese, with the same nickel content (16 per cent.) and 0·37 to 1·12 per

cent. carbon. It follows, therefore, that an addition of nickel increases the tensile strength to a greater extent than a corresponding addition of manganese.

Nickel steels with 0 to 12 per cent. of nickel and 0·3 per cent. carbon, and also those with 0 to 7 per cent. nickel and 0·95 per cent. carbon, with pearlitic microstructure, differ very little from ordinary carbon steels with the same carbon content in respect of tensile strength, ductility, yield point, elongation, hardness, and brittleness. On the other hand, with martensitic structure the limit of stretch and breaking strain are very high, if on the one hand, with 0·3 per cent. carbon, the nickel content does not exceed 12 to 30 per cent., and on the other hand, with 0·95 per cent. carbon, the nickel content lies between 0·6 and 18 per cent. The ductility and brittleness are here very low, whilst the hardness is extremely high. With  $\gamma$ -iron microstructure the ductility is remarkably high, provided the nickel content, in presence of 0·95 per cent. carbon, exceeds 18 per cent., the same also applying to cases where, with a low carbon content (about 0·3 per cent.), the nickel content exceeds 30 per cent. In both instances, however, the elastic limit and the brittleness are low, and the breaking strength medium; whilst, in respect of hardness, highly divergent and quite unexpected results were obtained, so that it was impossible to establish any definite standards. One remarkable point noticed was that the martensitic nickel steels of divergent carbon and nickel content did not attain maximum breaking strength and elastic limit with the highest carbon content. This demonstrates, in refutation of the old hypothesis, that the carbon content of nickel steels does not exert any noteworthy influence on the two properties in question.

Nickel steel is far more largely used in America than in Europe, although the actual saving from the use of such steel is very slight unless the steel contains at least 3·5 per cent. of nickel.

### C. CHROMIUM STEEL.

Chromium steels with 0 to 8 per cent. chromium and 0·5 per cent. carbon, or 0 to 5 per cent. chromium and 0·95 per cent.

carbon, and pearlitic microstructure, differ very slightly from ordinary carbon steels with a corresponding percentage of carbon, with regard to elastic limit, breaking strength, and elongation, and in this respect are analogous to the above-mentioned pearlitic nickel steels. The hardness increases with the chromium content, and is entirely independent of the carbon content, whilst the brittleness is far less than in carbon steels with the same carbon content.

On the other hand, chromium steels with 8 to 18 per cent. of chromium and 0·3 per cent. of carbon, as also those with 5 to 12 per cent. of chromium and 0·95 per cent. of carbon, of martensitic and troostitic structure, have a very high tensile strength, elastic limit, and breaking strength in comparison with pearlitic chromium steels, whilst their ductility is low, the hardness is extremely high, and the brittleness medium.

If the chromium content rises above 25 per cent. in presence of 0·3 per cent. of carbon, and over 22 per cent. with 0·95 per cent. of carbon, the elastic limit sinks considerably, whereas the brittleness increases in the same proportion and attains a very high value. In these cases the ductility and breaking strength attain medium values.

It is worthy of note that the tensile strength of chromium steels with troostitic structure is considerably less than when the structure is purely martensitic.

Steels low in chromium are pearlitic, those containing a medium percentage of chromium being martensitic. The microscopical examination of the high-chromium cemented steels, with the employment of picric acid as etching medium, is interesting. This treatment reveals white globules (probably a carbide), which seem to be dependent on a high carbon content as well as on a high chromium content, since the transformation of one structure into the other is governed by a definite ratio of chromium and carbon content. The hardness and elastic limit of pearlitic chromium steels are greater in proportion as the chromium content is increased in presence of a given content of carbon. Chromium steels with martensitic or troostitic structure exhibit exceedingly high degrees of hardness, elastic limit, and tensile strength, with low elongation and contraction.

In hardening, the pearlitic structure changes very quickly, and approximates to that of ordinary carbon steels. Annealing makes pearlitic chromium steels milder, as is also the case with martensitic chromium steel when hardened, small quantities of  $\gamma$ -iron being formed in both cases. An excellent hardening effect, with regard to the mechanical properties of chromium steel with double-carbide structure, is obtained at  $1250^{\circ}$  C., the structure having a white appearance. If quenching be effected suddenly, the carbide disappears completely, provided the chromium content has been sufficiently high.

Chromium steels with double carbide are very liable to fracture, and are therefore unsuitable for practical purposes. Those that are best adapted for practical use must be hardened, and exhibit pearlitic structure; the martensitic chromium steels, though very hard, cannot be recommended.

#### D. MANGANESE STEEL.

Manganese steels of pearlitic structure, with 0 to 7 per cent. of manganese and 0.3 per cent. of carbon, or 0 to 5 per cent. manganese and 0.95 per cent. carbon; as also those of martensitic and troostitic structure, with 7 to 15 per cent. manganese and 0.3 per cent. carbon, or 5 to 9 per cent. manganese and 0.95 per cent. carbon; and finally those of  $\gamma$ -iron structure, with 7 to 18 per cent. manganese and 0.3 per cent. carbon, or 5 to 11 per cent. manganese and 0.95 per cent. carbon, have approximately the same mechanical properties as the corresponding nickel steels mentioned above. Experiments to test the brittleness of pearlitic manganese steels gave the surprising result that these steels have about the same brittleness (a little less, if anything) as ordinary carbon steels.

A steel with 5.5 to 11 per cent. of manganese is more brittle and harder than one in which the manganese content is either higher or lower. It rarely happens that the hardness and brittleness of steels high in manganese are diminished, instead of being increased, by quenching; but this peculiarity may be observed in a manganese steel, low in carbon, when the manganese content reaches 19.5 per cent., and with as

little as 7·5 per cent. manganese in high-carbon manganese steels.

Generally speaking, a manganese steel consisting of martensite will exhibit great brittleness and high tensile strength; if the structure is polyhedral, the hardness is also very considerable.

### *E. TUNGSTEN STEEL.*

In the case of tungsten steels of pearlitic structure, and containing 0 to 15 per cent. of tungsten and 0·3 per cent. carbon, or 0 to 8 per cent. of tungsten and 0·95 per cent. carbon, the tensile strength, limit of stretch, and breaking load increase with the percentage of tungsten, whereas the ductility diminishes. The hardness is generally a little greater than that of ordinary carbon steels with a corresponding carbon content. The brittleness remains entirely unchanged, even when the percentage of tungsten exceeds 15 and 18 per cent. in presence of 0·3 and 0·95 per cent. of carbon respectively. With this high proportion of tungsten the only properties that vary are the elastic limit, ductility, and breaking load, the two first-named increasing very slightly, whilst the breaking load rises with the content of carbon and tungsten. Tungsten steels of pearlitic structure, and containing 0·25 per cent. carbon and over 9 per cent. tungsten, or 0·85 per cent. carbon and over 4 per cent. tungsten, increase in hardness as the tungsten content rises. Tungsten steels with double carbide attain sufficient hardness only when the carbon content is high, though their high fragility remains the same.

### *F. MOLYBDENUM STEEL.*

Molybdenum steel, with 0 to 4 per cent. of molybdenum and 0·3 per cent. of carbon, or 0 to 2 per cent. molybdenum and 0·95 per cent. carbon, gave results approximating closely to those furnished by tungsten steel in point of tensile strength, elastic limit, elongation, hardness, and brittleness when the ratio of added molybdenum was as 1:2·225 of tungsten content.



## G. VANADIUM STEEL.

On account of its admirable properties, vanadium now occupies a front position in the metal industry, and may rightly be termed "the metal of the future." At present the following compounds are prepared in the metal industry:—

- |                           |                                 |
|---------------------------|---------------------------------|
| 1. Aluminium-vanadium.    | 4. Ferro-tungsten-vanadium.     |
| 2. Ferro-vanadium.        | 5. Ferro-chromium-vanadium, and |
| 3. Ferro-nickel-vanadium. | 6. Nickel-vanadium.             |

Ferro-nickel-vanadium, ferro-tungsten-vanadium, and ferro-chromium-vanadium are particularly adapted for use in special steels. Ferro-vanadium imparts extremely useful properties to steel only when it is perfectly pure and free from extraneous components. Like carbon, vanadium increases the breaking strength and elastic limit of steel. A content of ferro-vanadium exceeding 2·1 per cent. lessens the ductility; but so long as the percentage of ferro-vanadium is below that limit, the ductility remains unchanged.

The following results demonstrate the great influence exerted by pure ferro-vanadium (0·2 per cent. to 2·1 per cent. ferro-vanadium) on the tensile strength of vanadium steels:—

Steel.	Tensile Strength.	Elastic Limit.	Elongation.
	Lbs. per Sq. In.	Lbs. per Sq. In.	Per Cent.
No. 1, Nature hard . . .	106,671	85,337	22·0
" Annealed . . . . .	186,319	163,562	8·5
No. 2, Nature hard . . . .	96,715	73,958	19·5
" Annealed . . . . .	169,351	140,806	7·5
No. 3, Nature hard . . . .	113,782	106,671	23·0
" Annealed . . . . .	192,008	172,096	6·9
No. 4, Nature hard . . . .	116,627	110,938	24·0
" Annealed . . . . .	194,853	177,785	5·5
No. 5, Annealed to 900° C. .	230,410	200,541	3·9
" " at 350° C. . . . .	213,342	184,897	59·0
" " " 450° C. . . . .	192,008	177,785	8·5
" " " 550° C. . . . .	177,785	156,451	15·0
" " " 650° C. . . . .	156,451	129,428	19·0
" " " 750° C. . . . .	130,850	106,671	30·0
" " " 850° C. . . . .	135,117	69,692	26·0

As is evident from this table, an addition of vanadium increases the tensile strength and elastic limit, without adversely affecting the elongation. Vanadium steel is far

superior to tungsten steel as a tool steel, retaining its hardness up to about  $2000^{\circ}\text{C}$ ., above which temperature the hardness gradually decreases.

The limits of proportionality and breaking strength increase, in the case of pearlitic steel, with the percentage of vanadium. The contraction and elongation increase but slightly, and only a little more than in ordinary steels with the same carbon content. They are also equal to the latter in point of brittleness, whilst their hardness is much greater. The influence of hardening is manifested to only a small extent in steels with a high content of vanadium (from 0.6 per cent. to 0.8 per cent. vanadium). On the other hand, in steels of pearlitic and cementitic structure, the limits of proportionality and breaking strength vary inversely with the vanadium content, whilst the toughness varies in direct ratio therewith. These vanadium steels are more brittle than ordinary steels with the same carbon content, but their hardness is only a little lower than the pearlitic vanadium steels. On being hardened by sudden cooling, the hardness diminishes when the vanadium content is low; but if cooling be gradual and retarded, a small percentage of vanadium gives increased hardness. On the other hand, when the whole of the carbon in vanadium steels assumes the condition of cementite, the limit of proportionality and the tensile strength diminish very considerably. Although, in such cases, the reduction of area and the elongation are greater than in vanadium steels with pearlitic and cementitic structure, these steels are, nevertheless, very brittle and are almost totally devoid of hardness. Their microscopical study shows great divergence of texture. Slow cooling has a favourable influence on the hardness of steels with a high vanadium content (from 0.8 to 0.92 per cent. vanadium), whereas sudden cooling produces no change, and has no appreciable effect on either the microstructure or mechanical properties.

Microscopically considered, all vanadium steels are highly interesting, and it is very difficult to judge them correctly, since even a low vanadium content is completely dissolved by ferrite, the solution becoming saturated when the vanadium reaches 0.6 per cent. Above this quantity, the vanadium unites with the pearlitic carbon to form a vanadium carbide,



and hence the more the pearlite recedes, the more clearly does the carbide come into prominence. Strangely enough, vanadium carbide was also found in the liquid mass, and all attempts at its dissociation proved unavailing. After pouring, it is found again in the upper portion of the ingot, so that it evidently has an ascending tendency. This drawback, which manifests itself particularly in an irregular composition of vanadium steels containing vanadium carbide, can be remedied by the addition of small quantities of aluminium to the charge of vanadium steel.

Pearlitic vanadium steel, containing 0 to 0.6 per cent. of vanadium and 0.3 per cent. of carbon, or 0 to 0.5 per cent. vanadium and 0.95 per cent. carbon, show an increase in elongation, hardness, and breaking strength, as the vanadium increases within the above limits, whereas the elastic limit and the brittleness decrease. If the vanadium content rises above 6 per cent. of vanadium with 0.3 per cent. of carbon, or over 10 per cent. vanadium with 0.8 per cent. carbon, the brittleness increases remarkably, the elastic limit, breaking load, tensile strength, elongation, and hardness falling considerably, as already stated.

For the manufacture of tool steel, only vanadium steel with less than 7.5 per cent. of vanadium is suitable, the best steels for this purpose being those containing 0 to 3.5 per cent. vanadium. The microscopical examination, using picric acid as the etching medium, shows that steels with 0.25 per cent. of carbon and less than 0.65 per cent. of vanadium exhibit pearlitic structure; the etching stains ferrite dark brown. As the vanadium content increases, the pearlite is found to contain well-defined white granules which, when the vanadium content is high (above 3.5 per cent. vanadium), displace the pearlite completely, so that nothing but the white granules remain visible. These white granules consist of the double compound of carbon with vanadium and iron. These results were given by case-hardened pearlitic vanadium steel.

The action of vanadium on ternary and quaternary steels consists, chiefly, in adversely affecting the deposition of the carbide in cooling. Chromium-vanadium steels, which, in spite of their high tensile strength, are far superior to nickel-

vanadium steels in respect of resistance to impact and torsion, are consequently highly suitable for motor car construction, and may be specially recommended for that purpose. If small quantities of vanadium be added to ternary and quaternary steels, their resistance to dynamic strains is considerably heightened, without loss of power against static strain. If the breaking strength of ordinary steel be increased by special heat treatment, the resistance to impact diminishes considerably. With chromium-vanadium steels, on the contrary, annealing raises the strength under dynamic tests to more than double that of the best carbon steels, and, at the same time, a high resistance to torsion becomes apparent. These properties may be still further improved by tempering and quenching in a mercury bath. Certain of these specimen vanadium steels, which were subjected by the author to suitable heat treatment by a special process, attained a tensile strength of 213,300 to 227,600 lbs. per square inch, some of them even to 247,500 and 261,000 lbs. per square inch, accompanied by extremely high resistance to dynamic stresses and torsion. Steel of this kind forms the ideal for future production, and will give new tone to the entire metal and steel industry.

#### H. SILICON STEEL.

Silicon steel of pearlitic structure, with 0 to 6 per cent. of silicon, has an exceedingly low tensile strength, elastic limit, elongation, and hardness—only the breaking strength and brittleness increasing with the rise in the silicon content.

Silicon steels with 6 to 8 per cent. of silicon, and of pearlitic and graphitic structure, as also silicon steels with over 8 per cent. of silicon and graphitic structure, are naturally precluded from industrial application, non-graphitic silicon steels alone being suitable for a limited number of purposes. As regards the transition from pearlitic to graphitic microstructure, the carbon content of these steels is devoid of importance.

In the case of iron, the toughness increases until the silicon content reaches 4·5 per cent. of silicon, any excess beyond that figure producing an opposite result. With more than 4·5 per cent. of silicon the hardness increases rapidly, and a tendency

to fracture is set up. Every increase of the elastic limit and tensile strength diminishes the elongation of silicon steels. With a silicon content of 4.5 per cent. of silicon, the elongation and reduction of section fall to zero.

### I. TITANIUM STEEL.

Titanium steel containing up to 12 per cent. of titanium behaves like ordinary carbon steels in respect of tensile strength, hardness, and brittleness.

The tensile strength of the metal is considerably increased by additions of titanium, especially in the case of cast iron, and for this reason titanium is preferable to nickel. In particular, it checks the formation of air bubbles, and thus furnishes better and more compact castings.

### V. CONCLUSIONS AND FINAL CONSIDERATIONS WITH REGARD TO THE SPECIAL STEELS EXAMINED.

According to Osmond's theory on the allotropic modifications of iron, the various mechanical properties of the iron-carbon alloys in the annealed and quenched condition are due to the circumstance that a larger or smaller quantity of  $\beta$ - or  $\gamma$ -iron is prevented by the quenching process, and also by the presence of carbon, from being transformed into mild  $\alpha$ -iron. Arnold's theory, on the other hand, implies that brittleness and hardening, produced by quenching, result from the formation of a very hard carbide,  $\text{Fe}_{24}\text{C}$ , hardenite, which is capable of taking up both the carbide  $\text{Fe}_3\text{C}$  and pure iron into solid solution. Although these divergent views have not yet been sufficiently elucidated, it has nevertheless been proved by experiment that steel may occur in the following conditions:

1. In the  $\alpha$  or primarily pearlitic condition (mild).
2. In the  $\beta$  or martensitic (very hard) condition, and
3. In the  $\gamma$  or austenitic (medium-hard, tough) condition.

The transition of pearlite into martensite occurs, in hyper-eutectoid steels, between  $710^\circ$  and  $730^\circ$  C. ( $\text{Ac}_1$ ); that of

$\alpha$ -iron into  $\beta$ -iron between  $730^{\circ}$  and  $750^{\circ}$  C. ( $Ac_2$ ), and the transformation of  $\beta$ - into  $\gamma$ -iron, as also that of martensite into austenite, between  $810^{\circ}$  and  $830^{\circ}$  C. ( $Ac_3$ ). In steels containing more than 0.89 per cent. of carbon in the hypereutectoid steels, all three transitions occur between  $710^{\circ}$  and  $730^{\circ}$  C.

When other metals—such, for instance, as molybdenum, titanium, manganese, chromium, nickel, and tungsten—are introduced into steel, the above-named transformation-points fall, so that, by suitable additions, it is possible to produce a steel that assumes the  $\gamma$ -condition at the ordinary temperature, and is therefore “self-hardening.” An exception with regard to this property is afforded by vanadium, since the double carbides resulting from the use of that metal cannot be destroyed by heating. The effect is produced in the simplest manner by adding manganese and nickel; whereas chromium requires greater care, because, when a certain percentage is exceeded, it forms with the iron double carbides that have to be destroyed by heating to  $1200^{\circ}$  C. The solution of the double carbide at this high temperature is effected by dissociation into chromium and carbon. If tungsten be used alone, the same brittle double carbides are formed, which again require to be destroyed by heating to  $1200^{\circ}$  C. before the metals just mentioned can exert their action, which is dependent on the lowering of the transformation-points. The tungsten steels require a certain temperature, which imparts the property that all steels, when cooled after heating, exhibit the same recalescence-points as the tungsten-free carbon steels. For  $Ar_1$  is the first to be affected by the lowering of the point of recalescence, and in the case of steels with a medium and low carbon content, the maximum point can be lowered to a maximum by heating to a little above the lowered temperature, the points  $Ar_3$  and  $Ar_2$  remaining uninfluenced thereby. Opinions differ considerably with regard to  $Ar_2$  and  $Ar_3$ . In the case of these steels, Arnold, in 1894, found that  $Ar_3$  was lowered by  $16^{\circ}$ , whereas  $Ar_2$  remained unaltered. On the other hand, Osmond believed originally, in 1890, that neither  $Ar_3$  nor  $Ar_2$  could be affected by tungsten; but he afterwards arrived at the conclusion that  $Ar_3$  disappears from its normal position. Conversely again,

with reference to Hadfield's steels, Osmond concluded, in 1903, that, in cooling from  $1300^{\circ}\text{C}$ .,  $\text{Ar}_3$  and  $\text{Ar}_2$  are lowered in turn, and consequently strive to coincide with  $\text{Ar}_1$ , although none of the curves given by this author shows any displacement of  $\text{Ar}_2$ . In the case of a number of test-bars (27 per cent. of carbon, 39 per cent. of tungsten), which had been cooled from  $1320^{\circ}\text{C}$ ., the present writer found that  $\text{Ar}_3$  was not present and  $\text{Ar}_2$  was sharply defined, whilst the lower point of recalescence was split up. He therefore came to the conclusion that  $\text{Ar}_2$  is not lowered in such steels in which this point appears unrestrictedly in normal circumstances. This view does not agree, therefore, with Osmond's conclusions related above. Although in 1894 he also inclined to the opinion that  $\text{Ar}_3$  gradually disappears (or seems to vanish), the author could only confirm this in one single instance—in the case of a test-bar with 0.139 per cent. of carbon and 3.78 per cent. of tungsten. Nevertheless, it must be objected that, as soon as the normal recalescence point  $\text{Ar}_3$  is eliminated, other irregularities make their appearance from  $700^{\circ}\text{C}$ . downward, forming the upper maximum of the lower recalescence point by concentrating themselves in an accurately definable retardation. It may, therefore, be assumed with certainty that, under certain conditions,  $\text{Ar}_3$  may form the upper portion of the lower retardation, provided that the initial temperature has been sufficiently high. On examining the appearance of the lower retardation with increasing percentages of carbon, it is found that the upper maximum gradually recedes until the saturation point is reached, whereas, on the other hand, the lower retardation appears as a single point directly the saturation point is exceeded. This noteworthy phenomenon is positively not at all dependent on the initial temperature exclusively, the author having found that in steels with 0.5 per cent. of carbon and 4.2 per cent. of tungsten, 0.61 per cent. carbon and 3.4 per cent. tungsten, 0.3 per cent. carbon and 4.0 per cent. tungsten, and 0.56 per cent. carbon and 2.9 per cent. tungsten, the lower point of recalescence splits up in an extreme degree when the heating has been carried above the lowered temperature. A remarkable fact, and one that is still inexplicable to the author, is that  $\text{Ar}_3$  is entirely absent in the case of mild steels.



Hence, if it be desired to displace the point  $Ar_1$ , the only way in which this can be effected is by allowing the initial temperature to rise with the increased carbon content. The interval of retardation attains its lowest limit simultaneously with the displacement of  $Ar_1$ —in mild steels. A rise in temperature, and sufficient time for the lowering to attain completion, are necessary in all cases where the carbon content is even slightly higher than 1 per cent.

Although, in a paper in the *Revue de Métallurgie*, Osmond assumes that during slow cooling the transformation points are depressed the more in proportion as the deviation from eutectic composition increased, the present writer has found, by numerous experiments, that the temperature at which the point is lowered must be regarded as solely a function of the tungsten content. This view is also shared by Swinden in his admirable work on carbon-tungsten steels, which he presented at the Spring Meeting of the Iron and Steel Institute in 1907.

With regard to the velocity of normal and accelerated cooling, the author came to the result that the critical point, when once it has been lowered, can no longer be raised again by prolonged heating below that lowered temperature, when the transformation has already occurred at a low temperature. In the converse case, the critical intervals make their appearance at different temperatures during cooling, even when the initial temperature is varied, and without reference to the carbon content. On the other hand, a higher percentage (above 0.31 per cent.) of manganese accelerates the rate of cooling, without it being possible thereby to raise the lowered critical point by prolonged heating. Every increase in the tungsten content has a restrictive effect by preventing the ordinary changes in constitution. Here a chemical and a physical alteration of properties occurs, persisting in the steel until the lower recalescence point has been reached, *i.e.* until the constitution has reverted to the normal condition. Hence a displacement of the critical point occurs in all cases. In steels of high carbon content, the ascent toward the lower recalescence point proceeds with remarkable quickness, a phenomenon that can only be explained by the rapid attain-

ment of a condition of equilibrium at the initial temperature. If the steel be cooled down from a high temperature, it takes a long time to reach a state of equilibrium when heated, whereas in molybdenum-chromium steels equilibrium is attained very quickly, if the temperature of  $883^{\circ}$  C. be not exceeded in heating this alloy. More gradual heating results in a retardation of the deposition of the carbide on cooling.

It is a typical property of tungsten steel, that after being cooled from about  $1190^{\circ}$  and  $1200^{\circ}$  C., with simultaneous appearance of a lower recalescence point, it can be restored to its normal condition by heating it up to any temperature below the low point. The opinion expressed by Carpenter and Osmond, that tungsten retards or prevents the change ordinarily occurring in the carbon steels, is therefore incorrect. Osmond supports his view on the fact that  $T_1$ —the temperature at which the recalescence point is duplicated—lies somewhat higher than  $Ac_3$ — $Ac_2$ — $Ac_1$ , at which, therefore, cementite begins to diffuse. If this were actually the case, we should only have a solution of cementite to deal with, which seems out of the question, since it would then be impossible to observe unaltered recalescence points as soon as the initial temperature differed from  $Ac_3$ — $Ac_2$ — $Ac_1$  by about  $500^{\circ}$  C., for the deposition of cementite tends to produce homogeneity, rather than inequality, in the carbon content. The inversion of the lower recalescence point usually occurs at  $Ac_1$ , a further transformation—entirely due to the tungsten—taking place at the lowering temperature. Consequently, if the cooling is effected from temperatures below the lowering point, only the first transformation can occur at  $Ac_1$ , whereas, on the other hand, the second makes its appearance at the lowering temperature.

The formation of the said brittle double carbides may also be prevented by a certain (not small) addition of chromium, nickel, or manganese. Only the double carbides formed when vanadium is used cannot be decomposed by heating; and it follows, therefore, that vanadium is unsuitable for self-hardening, high-speed steels. Another very remarkable property of the special steels is that the annealing temperature of the resulting alloys of the metals just named is far higher than



that of the ordinary carbon steels. The author found that the annealing temperature of chromium steel is dependent on the chromium content, increasing in the same ratio as the chromium is raised, whilst the lowering of the conversion temperature varies inversely therewith. The cause of this peculiar behaviour has not yet been sufficiently cleared up for the author to report more fully upon it at present.

## VI. GENERAL DESCRIPTION OF THE METHODS AND APPARATUS ADOPTED FOR THE EXAMINATION OF SPECIAL STEELS.

In all the experiments great care was devoted to obtaining ingots free from defects. The material employed was American "washed iron," and the ferro-tungsten, ferro-manganese, ferro-nickel, &c., used in each case was prepared specially. The finished ingots had an average measurement of 30 by 30 millimetres (1.18 inches), and weighed 8.257 kilogrammes. They were partly rolled to round bars of 15 millimetres (0.59 inch) diameter, partly cast and partly hammered down. In many of the test-bars the percentage of sulphur was rather higher than desirable, though in no case was the permissible limit exceeded. Special attention was bestowed on the nitrogen content of the steels used, the mean percentage for the whole of the test-bars being 0.11 per cent. The bars used for the mechanical tests were heated to  $950^{\circ}\text{C.}$ , maintained at that temperature for 15 minutes, and then cooled down slowly in the air, in order to equalise any irregularities, and to free them from all stresses produced by rolling. The specimens for the tensile tests were lathe-turned to a diameter of 10 millimetres. The elastic limits given in the various tables refer to the loads under which permanent elongation of the bar was produced. The bars used for the pressure tests measured 14 millimetres in diameter (153.938 square millimetres sectional area) and 30 millimetres in length. The load was gradually increased to 26.800 kilogrammes. The bars for the alternating test were 125 millimetres long

and 8·5 millimetres diameter, and were tested in the machine described by Professor Arnold.\* The number of the alternating stresses amounted to 640 per minute, and was registered automatically in such a manner that the registration ceased immediately on the rupture of the test-bar. The specimens for the cold-bending test were 100 millimetres long and 8·5 millimetres in diameter. They were embedded to the depth of 50 millimetres in a block, and were bent in such a manner that the radius of curvature measured 5 millimetres. The angles of flexion were  $180^{\circ}$ ,  $140^{\circ}$ ,  $100^{\circ}$ ,  $85^{\circ}$ ,  $75^{\circ}$ ,  $45^{\circ}$ , and  $30^{\circ}$ .

The apparatus used for taking the cooling curves was that fully described and illustrated by Professor Arnold,† and is therefore well known. The thermo-element used in the tests was composed of platinum, and platinum containing 10 per cent. of rhodium, and was connected direct to an astatic galvanometer. The test-bars were 15 millimetres in diameter and 100 millimetres long. In order to ensure absolute contact between the thermo-element and the steel specimens, an insulating recess, 55·5 millimetres long and 12·5 millimetres in diameter, was constructed of fireproof siliceous material, the thermo-element being then fitted into a recess, forming a continuation of the preceding one, and measuring 3·1 millimetres in diameter. The specimens were heated beforehand in a coke-furnace. The curves were taken in vacuo, the individual test-bars being heated about 10 to 15 times up to  $1250^{\circ}$  C. The usual rate of heating was 7 millimetres per second, corresponding to an increase in temperature of  $3\cdot5^{\circ}$  C. At the commencement of the tests, the mean rate of cooling was 9 to 12 seconds per millimetre; and towards the close, 18 to 19 seconds per millimetre at  $550^{\circ}$  C. Between each two successive heats the test-bars were cooled down to about  $150^{\circ}$  C. The speeds were measured by a chronograph. The two thermo-elements consisted of platinum, and platinum with 10 per cent. of rhodium, and were standardised by means of water, sulphur, copper, potassium sulphate, and silver. For the microscopical analysis, the sections of the ingot and billet

\* Paper read before the British Association at Cambridge in 1904; *The Engineer*, vol. xcvi. p. 227.

† *Proceedings of the Institution of Civil Engineers*, vol. cxx., 1895-96.

were polished, according to custom. A 3 per cent. solution of nitric acid in alcohol was employed as the etching medium.

Another method of hardening practised was the following: Sections 8 millimetres thick were cut from the round bars under examination, and heated in an electrical furnace to  $1200^{\circ}\text{C}$ ., the temperature being measured with a platinum-iridium element, the junction of which was placed in direct contact with one side of the test section. On the other side of the section was a small hole, for the reception of an iron wire, held in place by an asbestos plug, and thus kept separate from the platinum-iridium element. The specimens were maintained at  $1200^{\circ}\text{C}$ . for 5 to 8 minutes, and then drawn out by means of the iron wire and quenched in a current of air. The average rate of cooling of the specimens was about 30 seconds, below red heat; and in about 2 to 3 minutes they had receded to ordinary temperature. The sections hardened in this manner were then polished, etched, and their structure examined. For the annealing test, only such bars were used as exhibited a white, polyhedral structure after the above quenching. In order to determine the influence of annealing on specimens quenched in the air, the specimens were heated for 60 minutes in an electrical furnace at an extremely uniform temperature. The unfavourable circulation of air in the furnace was prevented by closing the ends of the heating tube, by which means it was possible, without any great trouble, to regulate the temperature of the heating resistance with accuracy, so that the temperature remained constant to within  $2^{\circ}$  to  $3^{\circ}$ . When necessary, the individual specimens were examined within a range of temperature of  $400^{\circ}$  to  $900^{\circ}\text{C}$ ., and then cooled down to room temperature, in the furnace, for the microscopical examination. If the annealing effect proved incomplete at a given temperature, the next experiment was performed with a temperature  $60^{\circ}$  higher, and so on until the steel was found to be fully annealed. The test-bars were then wet-polished on an emery disc, being afterwards given a finishing polish, and etched with a 1 per cent. solution of nitric acid in absolute alcohol. With some bars the author noticed an increase in the size of the polyhedra with rising quenching temperature, and in such cases a more prolonged etching was

required. The average time needed for etching the structure of the fully heated bars was about 30 seconds; whereas other specimens, with remarkably large polyhedra, took about 1750 seconds to etch. With specimens that were only partially annealed, the time of etching varied between 110 and 200 seconds.

In some of the bars the annealing was examined, in order to ascertain the influence of the initial hardening temperature on steels in which the effect of annealing could be traced by the alterations of structure. These were steels that had been previously cooled from high temperatures in a current of air and hardened. The contingency was also borne in mind of the quenching temperature being higher than that at which the depression and fission of the critical interval occur. In such cases the experiment was performed at various quenching temperatures between  $1000^{\circ}$  and  $1200^{\circ}$  C., each specimen being maintained at the requisite temperature for 15 minutes previous to quenching.

## VII. THE THEORY OF THE FERRO-CARBON ALLOYS AND HIGH-SPEED CUTTING STEELS. THERMAL AND MECHANICAL TREATMENT OF ORDINARY CARBON STEELS.

### A. HIGH-SPEED STEELS.

The cheapest method of obtaining a good high-speed cutting steel is by an addition of manganese, since this metal does not produce any double carbides that have to be decomposed. The amount of manganese added to these steels must be at least sufficient for the transformation into a  $\gamma$ -steel, in order to raise the annealing limit as high as possible. Since steels containing carbon (hypereutectic) are readily transformed into  $\gamma$ -steels, these are advisable, in view of the consumption of manganese, provided the necessary care be taken, since, as demonstrated experimentally by Guillet, these steels readily become hard and brittle, *i.e.* martensitic. In practice, however, preference is given to chromium-tungsten steels, and especially to chromium

steels, it being necessary to take into consideration the transformation temperature and the raising of the annealing temperature, whereas the double carbides formed with the tungsten are not fully decomposed by heating, and the percentage of undecomposed carbides increases with the tungsten content, whereby the steel is subjected to a lower annealing temperature. With a carbon content of 0.78 per cent. C., the addition of chromium may attain 12 per cent., and with 0.25 per cent. of carbon 17.5 per cent., without any formation of double carbides, whereas in the case of tungsten, such formation is observed with a percentage of 4.2 per cent. of tungsten. At the same time, an increase in the tungsten content reduces the cutting speed, whereas an increase in the chromium content has the opposite effect. On the other hand, if an almost pure chromium steel ( $\text{Cr}_8$  to  $\text{W}_3$ ) be prepared, an excellent high-speed steel is obtained, which is very difficult to work, owing to its martensitic structure. A high-speed steel that can also be classed as good, is obtainable with a still higher percentage of chromium (about  $\text{Cr}_{15}$  to  $\text{W}_2$ ), which steel, although, strangely enough, a  $\gamma$ -steel, has behaved well in practice. Taylor, and especially Carpenter, hold the opinion with reference to the investigation of special steels, that the action of chromium is entirely restricted to effecting the complete solution of the double carbide resulting from the transformations effected by tungsten. In his own researches in high-grade tungsten and chromium steels, the present author found confirmation of Guillet's opinion, that the only way in which steel rich in tungsten can become an ideal high-speed steel is by converting it into self-hardening steel, by simple heating to  $1200^\circ\text{C}$ . after working it first in the form of double-carbide steel, in which condition it is readily workable. In such case, however, any addition of chromium would make the steel unworkable from the outset; but this difficulty can be overcome by adding sufficient chromium at the start to produce the  $\gamma$  form. In this condition it can easily be worked, and, according to Guillet, is not at all too soft for use as high-speed steel. The same conclusion was formed by Taylor in his researches on these steels. Again, with an addition of 18.5 per cent. of chromium, we obtain the soft double carbides, which, as



already stated, also appear with a content of 4·2 per cent. of tungsten, and these, too, must be destroyed by heating to over 1200° C. In the manufacture of high-speed steels, these peculiarities form an inducement to give preference to chromium and tungsten over manganese and nickel, more especially since a very large addition of nickel is necessary for a good high-speed steel. The percentage of chromium and tungsten depends entirely on the carbon content: the higher this latter the smaller the proportion of chromium and tungsten necessary to furnish  $\gamma$ -steel—a saving in cost that should not be under-estimated. It would therefore be advisable to prepare an alloy of the following composition: 0·85 per cent. carbon, about 9·5 per cent. chromium, and 3·5 per cent. manganese, since, with this high carbon content, a double carbide is formed already with 9·5 per cent. of chromium, the relatively large addition of manganese then greatly accelerating the attainment of the  $\gamma$  condition. These alloys must be prepared with great care and attention, owing to the high importance of decomposing the brittle double carbide as completely as possible, in order that the carbon and tungsten may be liberated and exert their inherent properties of hardening the metal and depressing the conversion temperature,

As a rule, the addition of molybdenum cannot be recommended in the production of high-speed steels. Most of the specimens of molybdenum steel prepared by the author were of irregular constitution throughout and brittle. A further drawback in the production of these steels is the necessity for extremely accurate determination of the degree of heating below the melting-point when usable molybdenum cutting steels are to be produced. It is worthy of note that molybdenum can exert the same effect as tungsten when the relative proportion is as 1 : 2·225.\*

According to the author's opinion, silicon and titanium steels are of minor importance as high-speed steels when the silicon content exceeds 0·18 per cent., and the titanium content 12 per cent. With the former, a metal that is as free as possible from sulphur and phosphorus must be used. The mechanical and physical properties of titanium steel with

\* See "Molybdenum Steel," p. 31, *ante*.

12 per cent. titanium are almost identical with those of ordinary carbon steels.

Despite our accurate knowledge of the chemical composition and analysis of the special steels, practical trial still remains the most reliable and surest method for judging them; and careful handling of the steel, and accurate melting and pouring, constitute fundamental conditions for their production. In the author's opinion, and from the results of his experiments, a low percentage of manganese (about 0.15 per cent.) should be present in all high-speed steels. The secret of success often lies in the most careful compliance with and performance of these fundamental conditions.

### B. STRUCTURAL CHANGES IN SUPERHEATED STEEL.

With regard to the structural changes in superheated steel during reheating, and the frequently contested circumstance that steel which has been rendered coarse grained by superheating can be reconverted into a finely granular condition by reheating at a suitable temperature, the following particulars may contribute to the elucidation of the matter.

If the structure of a steel has been coarsened by strong superheating, and the steel be then cooled and reheated, a separation of cementite occurs at the critical point  $Ac_1$  during this reheating. A segregation of cementite occurs, however, at a temperature just below  $Ac_1$ , small rings being formed as a result of surface tensions. If, however, the reheating be carried to over the point  $Ac_1$ , the cementite is gradually transformed into martensite. According to a diagram by Roberts-Austen, it would seem as though  $Ac_3$  were the temperature at which the last traces of the coarse reticulation disappear. This diagram further shows that in cases where steel of problematical carbon content is cooled hypereutectically [from about  $950^\circ \text{C. (Ar}_3)$  to  $690^\circ \text{C. (Ar}_1)$ ], at which temperature the material consists mainly of martensite, the solvent power of the latter with relation to cementite diminishes to such an extent that the cementite is precipitated within the mass of martensite and forms a network. The size of this network is approximately proportional to the temperature from which



the steel has been cooled. Although the reabsorption of the cementite into the martensite proceeds inversely, the phenomenon is similar to that referred to at first. The solvent power of the martensite increases directly the temperature rises from  $Ac_1$  towards  $Ac_3$ , the cementite being absorbed by the martensite and consequently disappearing gradually. When hypereutectic steel is heated for such a length of time as to be completely transformed into martensite, and is then cooled (whereupon cementite and pearlite may be formed), the cementite network will appear coarser in proportion as the temperature is higher. How far the thickness of the network is dependent on a progressive alteration of the martensite, or on polarisation within the cementite, is an important problem that has not yet been settled. Up to the present no thickening that does not contain cementite has yet been observed in martensite, this non-success being probably due to lack of the requisite means for separating the martensite granules from each other.

Sauveur and Howe, in their experiments, found that the granules continue at temperatures considerably higher than the point  $Ac_3$ , and therefore at a temperature at which cementite cannot be detected. Howe is of opinion that the size of the granules is dependent on polarisation in the martensite, this conclusion being arrived at from the fact that, in cooling down from temperatures above the point  $Ac_3$ —the temperature at which the precipitation of cementite begins—the cooling temperature of the point  $Ac_3$  nevertheless remains the same, no matter how high the temperature may have previously been raised above  $Ac_3$ .

When superheated and re-cooled steel is heated again to temperatures between the points  $Ac_1$  and  $Ac_3$ , for example  $800^\circ \text{C}$ ., a quantity of cementite is dissolved equal to that which was precipitated from the martensite between  $800^\circ \text{C}$ . and  $Ar_1$  during the preceding cooling. The dissolved cementite is then disseminated in the surrounding martensite, and a new cementite network is formed. The solvent power of the martensite is thereby diminished, and the dissolved cementite is reprecipitated, provided the steel has been cooled again. Pearlite settles very unsatisfactorily in steel, when the tem-

perature has been raised to only a small extent above the point  $A_{c_1}$ ; but if the heating temperature be raised, an improvement in this respect is obtained, the reheating above the point mentioned causing the transformation of pearlite and cementite into martensite. This renders it very difficult for the pearlite, and also the cementite, to distribute and form a homogeneous mass after the change into martensite. The cause resides in the resulting solidification of the metal, and in the relatively low temperature at  $A_{c_1}$ . If, on the other hand, the heating be checked at once above the point  $A_{c_1}$ , the metal retains the traces of its former pearlitic structure. If, now, the martensite be transformed into pearlite during the cooling of this heterogeneous substance, it is highly improbable that the new pearlite will be deposited uniformly, a necessary condition of good deposition being that the mass from which the pearlite is formed should be nearly homogeneous, since, under the conditions mentioned, it may be assumed that the new pearlitic structure will cross the old one. If this assumption be correct, then the steels that have reached a temperature only a little higher than  $A_{c_1}$  must exhibit a trace of the old pearlitic structure, whereas, on the other hand, those that were heated sufficiently high must be free from same. This conclusion was fully confirmed by the investigation of the surfaces of fracture and the microstructure of the test-bars examined.

### C. STATE OF EQUILIBRIUM OF THE "IRON-CARBON" SYSTEM.

The great progress in our present knowledge on the state of equilibrium of the iron-carbon system opens a field, that has not yet been investigated to any great extent, in the examination of iron-carbon alloys. If our researches be undertaken from this modern physico-chemical standpoint, many hitherto inexplicable phenomena will be revealed in an entirely different light, and erroneous conclusions will be precluded. The first contribution to a diagram in connection with this system was illustrated by graphical means in a scheme of solidification published by Sir William Roberts-

Austen in an appendix to the fourth report of the Alloys Research Committee, on 4th February 1897. This diagram set out a purely empirical arrangement of the known work that had been performed on the melting and critical temperatures of iron-carbon alloys. The authors of the work known up to that time were Osmond and Roberts-Austen. The diagram was supplemented in August of the same year by Bakhuis Roozeboom, and published by him in the *Zeitschrift für physikalische Chemie*.<sup>\*</sup> The principal alteration in the Roberts-Austen diagram consisted in the addition of the line Aa, which Roozeboom considered necessary from a theoretical standpoint, although he had not been able to determine it experimentally. This line gives the carbon content of the mixed crystals deposited along AB; and at the same time it shows the maximum temperatures at which alloys with 0 to about 1·8 per cent. of carbon occur in complete solidification (see Fig. 2).

The divergent conclusions that may be formed with regard to this system may be gathered from the following.

The most recent investigations show that graphite must be regarded as the stable form of the equilibrium at high temperatures, but when we turn to cementite, a divergence of opinion arises. Experimental investigations on the behaviour of cementite lead to the assumption that this substance corresponds to a stable condition of equilibrium, since it can be detected in nearly all iron-carbon alloys. In spite of thermal or mechanical treatment of the material, cementite has always been found. Nevertheless, the searching investigations of A. Portevin † led him to conclude that cementite is present only in a labile condition of equilibrium. Accordingly, the condition diagram of the iron-carbon alloys is clearly determined by the state of equilibrium of a stable graphitic system and a labile cementitic system.

In the former system the separation of mixed crystals,  $\gamma$  with 9 to 2 per cent. of carbon (*a*), occurs along AB, and the deposition of graphite along BD. Hence, melts with 4·3 per cent. of carbon (eutectic point B) solidify completely to a

<sup>\*</sup> *Eisen und Stahl vom Standpunkt der Phasentheorie.*

† *Revue de Métallurgie*, No. 11, Nov. 1907, p. 993.

eutectic graphite-mixed crystals with 2 per cent. of carbon, this solidification terminating at  $AaC$ . If, however, the cooling be sufficiently protracted, the melt contains mixed crystals between  $A$  and  $a$ , in the eutectic between  $a$  and  $B$ , and finally graphite in the eutectic between  $B$  and  $C$ . The phase-rule would characterise this occurrence as mixed crystals and mixed

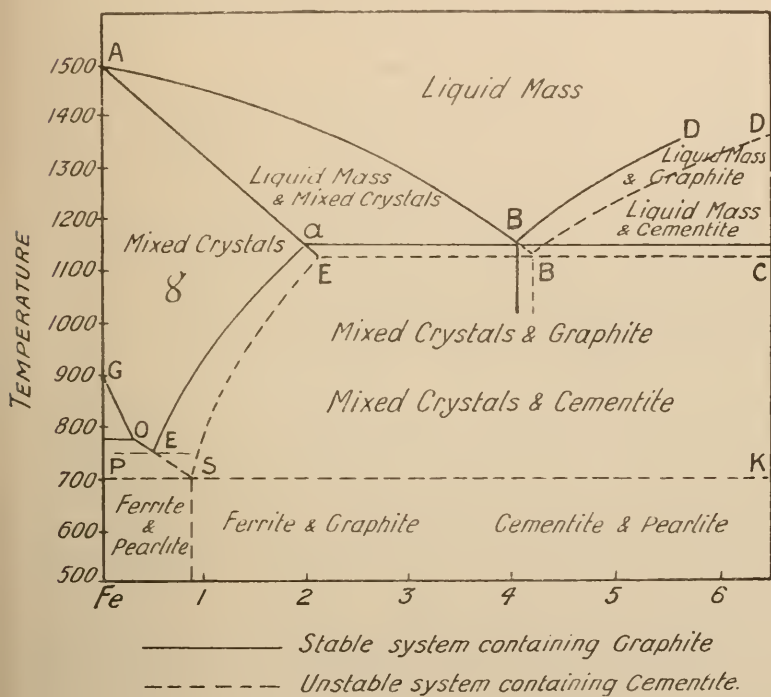


FIG. 2.

crystals + graphite. In addition to these two phases there is also a ferrite phase, in which the ferrite separates from the mixed crystals. Hence, on the one hand, we have the state of equilibrium: mixed crystals plus graphite, and on the other, mixed crystals minus ferrite. With 0.85 per cent. of carbon the deposition of ferrite from the mixed crystals consequently occurs at different temperatures from those at which  $\alpha$ - or  $\beta$ -iron would be separated, with the same carbon content.

Again, if it be remembered that neither the magnetic  $\alpha$ -form nor the non-magnetic  $\beta$ -form dissolves carbon, we arrive at the conclusion that the curve of the deposition of ferrite from the solid solution is also the same as the curve of the conversion of  $\alpha$ - or  $\beta$ -iron into  $\gamma$ -iron; and this gives the further deduction that the point E corresponds to a eutectic, ferrite minus graphite. Ferrite and graphite would only be found on the complete attainment of the state of equilibrium. Up to the present, however, cementite alone has been found corresponding to the labile system.

With too rapid cooling, or in presence of certain extraneous bodies, we nevertheless find carbon in the labile cementitic system as the result of a supersaturation with graphite. The cementite would therefore separate along the curve B'D'. Although the separation of the mixed crystals remains unaltered, the point B' corresponds, after complete solidification, to the formation of a mixed-crystal + cementite eutectic. According to Charpy and Grenet, the line E'C' is 20° C. below EC. With 0 to 0.85° C., ferrite separates from one of the two existing phases, cementite and mixed crystals, and indeed from the latter. The evolution of heat observed by Carpenter and Keeling at 800° C. was attributed by Roozeboom to a transformation of the cementite. The author is of opinion that this disengagement of heat in the decarburised outer stratum of the specimens is induced by the conversion of  $\beta$ -iron into  $\alpha$ -iron. Pearlite (cementite plus ferrite) separates out along E'S.

In the paper by A. Portevin, referred to above, the following reasons are given for the existence of both systems, and these reasons are confirmed by the researches of the author.

Portevin asserts that hardening carbon is formed as the dissociation product of cementite after prolonged heating above 1000° C., which product differs from graphite merely in the size and shape of the lamellæ. The latest researches of Sauveur and Wüst confirm this fact. Portevin believes that an influence is exerted by the rate of cooling, white iron being formed when cooling is rapid, grey iron by slow cooling.

Since the saturation line ( $\alpha$ E) of the solid solution for graphite is entirely above that of the solid solution for



cementite ( $E'S$ ), he believes, with reference to the position of  $aE$ , or  $E'S$ , that the state of equilibrium of the solid solution for cementite ( $E'S$ ) is labile, and since  $EBC$  (formation of eutectic, cementite + mixed-crystals) is also below  $aBC$  (formation of the eutectic, graphite + mixed-crystals), confirmation is afforded of his assumption that cementite is formed during the progress of cooling.

Wüst, who employed very pure iron-carbon alloys for his experiments, did not observe any disengagement of heat at all at  $1000^{\circ}$  C. in cooling. In his admirable treatise on the equilibrium and solidification structures of the iron-carbon system,\* Benedicks explains the disengagement of heat at  $1000^{\circ}$  C. as follows: Since the deposition of cementite on the surface of the liquid melt occurs when the mixed crystals have been deposited therefrom, the cementite of the eutectic corresponds to a crystal nucleus with a supersaturated interior. On the supersaturation being abolished, heat is liberated, and at the same time a deposition of small cementite lamellæ occurs in the mixed crystals. Since this cementite is not stable, it must be endothermic. This phenomenon must not be neglected in investigations, although Osmond believes this cementite to be exothermic. Nevertheless, graphite is the form of a labile state of equilibrium. The cementite formed as the result of supersaturation has a tendency to decompose into graphite, when the elevation of temperature, *i.e.* the degree of passive resistance exerted, is sufficiently high. The prolongation of reheating increases the amount of graphite deposited, and this becomes the more complete, the more protracted the cooling, each system striving to attain equilibrium as the final condition. In perfectly stable systems, on the other hand, the passive resistances increase the more, as the temperature falls, in proportion as the deposition of graphite has proceeded more rapidly during reheating.

In the melt, the carbon is dissolved as iron carbide, and it is deposited therefrom as such on recooling, though during the final decomposition it assumes the form of graphite, which then appears in the stable form.

\* "Ueber das Gleichgewicht und die Erstarrungs-strukturen des Systems Eisen-Kohlenstoff," *Metallurgie*, Nos. 12 to 14, III. 1906, pp. 8, 9, 10 *et seq.*



Similar results were obtained in the experiments of Wüst and Goerens. The researches of the former showed that the amount of graphite deposited is a function of time, and increases when the melt is left to stand at the eutectic point. Goerens' experiments also confirmed the primary separation of cementite. He found that, in an iron rich in carbon (7.5 per cent. of carbon), the large primary graphite crystals have no connection with the eutectic, mixed-crystals + graphite, but that they are separated from the eutectic by a perfectly non-graphitic margin.

The direct thermo-chemical determinations performed by Campbell, Troost and Hautefeuille, and also the syntheses of Moissan, show clearly that the deposition product, cementite, is endothermic and metastable, and not, as assumed originally by Roozeboom and Osmond, exothermic, and stable at low temperatures.

As already mentioned by Benedicks, in his admirable and thorough paper alluded to above, Roozeboom's diagram requires modification and simplifying by omitting the line representing the reversible reaction: mixed-crystals + graphite = cementite.

#### D. ALTERNATING STRESSES.

Interesting observations in connection with alternating stresses were made by the author in a series of steels, heated to temperatures between 550° and 1150° C. and then gradually cooled. The lines of slip, occurring as indications of fatigue under alternating stresses, sought a path chiefly through the ferrite. Specimens which were heated to 800° C. exhibited a rough superficial appearance with numerous wrinkles, the lines of slip being short and forming stepped gradations. With higher heating temperatures the roughness of surface was less perceptible, and the lines of slip were longer and less step-like. In the examination of the lines of slip it is essential that information should have first been gained about the structure of the crystalline grain, this facilitating reconstruction of the relation of same to the surface under observation and to the direction of the force. The distribution of force in the crystalline grain depends on the state of internal stress

and the distribution of the external tension in the interior of the crystalline grain. The effects of force may be plotted, graphically, as components, the resultants of which naturally vary from point to point, and are therefore different. This very common observation with regard to steels of equal composition but different heating temperatures and length of cooling, led the author to the opinion that variations in the modulus of elasticity must appear from one crystalline grain to another, and that the modulus of elasticity in one and the same crystalline grain is variable with the change of direction. The assumption of this possibility renders the existence of a constituent probable, but since the elastic properties of such a constituent are still entirely unknown, nor have they been mentioned, to the present writer's knowledge, by other workers, it is very difficult, *a priori*, to institute exact investigations in respect of this probability. The step-like arrangement of the lines of slip, which Osmond called "curvate," depends on the unequal distribution of force, the slip of force affecting only a small portion of the surface examined. If the crystalline grain resists this slip of force, and the latter does not spring within the next instant to an adjacent point, to a gliding plane different from the first one, then we have lines of slip of nearly straight delimitation; in the other case, however, these lines of slip assume a stepped appearance.

Researches on the fatigue of normal bars showed numerous lines of slip, whereas few were visible in superheated steels. This fact indicates that the permanent deformation modifying the material is uniformly distributed in normal bars, whereas, in the superheated steels, the deformation is localised. The low power of resistance of the latter also favours this hypothesis. Hence, all metals exhibiting very decided step-like lines of slip, when other conditions are equal, possess higher powers of resistance toward inelastic deformation than such as exhibit less stepping in the lines of slip.

#### E. PHENOMENA OF HARDENING.

The observations made and results obtained in connection with the hardening of the specimens examined, led the author

to the opinion that the chief cause of the hardness of hardened steel consists in the allotropic modification of the iron, since the change in the properties of the steel is accomplished before the transformation of the carbon. It was found that between the interval (conversion of the allotropic iron into the  $\alpha$ -form and the conversion of the dissolved carbon into carbide carbon) the carbon present in the  $\alpha$ -iron passes into solution. Heyn and Bauer gave the name osmondite to this solution of carbon in  $\alpha$ -iron. In specimens annealed at various high temperatures and treated with dilute sulphuric acid, the acid was found to have acted most strongly in those annealed to  $400^{\circ}\text{C}$ . In examining similar specimens, Heyn and Bauer found that, in addition to the hardening carbon—which, as is well known, is partly liberated in the form of gas during the dissolving of the specimen in dilute sulphuric acid—and the cementite left behind as residue, another form of carbon (termed by them, osmondite carbon) is left in the residue. Osmond, on the other hand, regards this carbon as originating in very finely divided cementite that has been decomposed by the very dilute sulphuric acid. The author instituted researches on this point, but in general without any decisive results, though he regards the opinion of Heyn and Bauer as confirmed. The formation of carbide is specially hindered by manganese and chromium, which are good hardeners inasmuch as they induce more of the contained carbon to remain behind as hardening carbon. Silicon and tungsten act in the opposite sense, *i.e.* they facilitate the formation of carbide.

Some connection exists between the electrical conductivity of iron and the degree of hardness, inasmuch as the modification of one of these properties is accompanied by changes in the other. This connection was established by experiments with Gysinge electro-steel, produced from Dannemora ore, and resembling English crucible steel.\* The resistance to conductivity of the steel and iron was calculated, from the observations made, by the formula:

$$\sigma = 7.6 + 26.8 \Sigma \text{Cu} - \Omega \text{ per cubic centimetre,}$$

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\* "Researches at the Physical Institute of the University of Upsala," *Zeitschrift für physikalische Chemie*, 1902, pp. 40 and 345.

in which  $\Sigma C$  represents the sum of the carbon values of the dissolved substances, expressed as percentages. If  $\Sigma C = \text{zero}$ , the resistance of absolutely pure iron is obtained, viz. 7.6.

Equivalent quantities of different dissolved substances increase the resistance to conductivity to an equal extent. The increase in electrical resistance due to hardening disappears when the maximum amount of osmondite has been formed, namely at  $400^{\circ} \text{C.}$ , whence it follows that the electrical resistance of osmondite is the same as that of pearlite. C. Benedicks\* proceeds from the standpoint that the hardness of a metal is chiefly influenced by the substances that are dissolved in that metal. In addition to this qualitative relation comes the quantitative rule that equivalent quantities of the dissolved substance produce the same increase in hardness, provided they are homogeneously dissolved. Accurate determinations of this kind have shown, with reference to the content of carbon dissolved in iron, that, with a surplus of carbide carbon, 0.27 per cent. of carbon can be detected as hardening carbon in the iron. This value therefore gives the tension of solution of carbon in iron (martensite). According to the paper read by Van t'Hoff, in 1901, on tin, gypsum, and steel from a physical standpoint, a carbon-iron compound of the composition  $\text{Fe}_3\text{C}$  (cementite) undergoes a pyrochemical reaction at about  $1000^{\circ} \text{C.}$ , being decomposed into graphite on the one hand, and a solid solution of carbon and iron (containing 1.8 per cent. of carbon) on the other. Furthermore, steel contains, as morphological elements, the two modifications of iron,  $\alpha$ - and  $\beta$ -ferrite (the mutual conversion temperature of which is  $850^{\circ} \text{C.}$ ), and pearlite. This pearlite is regarded by Van t'Hoff as a mixture, in constant proportions of cementite and  $\alpha$ -ferrite, associated with the solid solution (containing 0.8 per cent.) of carbon in  $\beta$ -ferrite. On the other hand, according to Osmond,† pearlite consists of lamellæ of cementite and another constituent, which he specifies as sorbite, since it was stained a dark colour by iodine, which is

\* "Researches at the Physical Institute of the University of Upsala," *Zeitschrift für physikalische Chemie*, 1901, pp. 36 and 529.

† *Bulletin de la Société d'Encouragement*, 1900, pp. 6 and 652; and 1895 pp. 10 and 480.

not the case with either cementite or ferrite. By the aid of the determination of its electrical resistance, C. Benedicks\* identifies this sorbite with the solution of carbon in iron, containing 0.27 per cent. according to Van t'Hoff. According to the same author, one form of pearlite lamellae may consist, in steels low in carbon, of more or less pure iron-ferrite, so that a distinction would have to be drawn between two types of pearlite. Benedicks,† however, explains the difference in the hardness by the quantity of dissolved carbon (hardening carbon) that remains in this condition after different methods of quenching. Thus, for instance, a steel with 1 per cent. of carbon will contain 0.27 per cent. of dissolved carbon after slow cooling; but if the steel be heated to 600° C. and cooled suddenly, 0.4 per cent. remains in solution, so that a lower degree of hardness is obtained in this case. If, on the other hand, the temperature be raised to 700° and 800° C., the greater portion of any carbon present remains dissolved, even after rapid quenching to room temperature, so that the degree of hardness is very high. Accordingly, the existence of this solution at the ordinary temperature must be regarded as the cause of hardening; from which it follows that the dilute solid solution, to be looked upon as the cause of hardening, is formed by a pyrochemical process. The same principle may probably be applicable to the hardening of nickel steel as well. P. Lebeau‡ prepared a series of chemical compounds between iron, silicon, copper, and manganese, by pyrochemical means, by smelting in a Perrot furnace. At least, he attributes to certain of these compounds, such, for instance, as those of manganese with silicon, and of this metalloid with iron, a composition that he expresses by the formulæ:  $\text{SiMn}_2$ ,  $\text{SiMn}$ ,  $\text{MnSi}_2$ ; and  $\text{SiFe}$ ,  $\text{SiFe}_2$ , and  $\text{Si}_2\text{Fe}$ . Nevertheless, Lebeau himself regards the one constituent as a liquid in which variable quantities of the other can be dissolved, according to the temperature. He therefore admits, in the first place, that the one constituent must be credited with a tension of solution in the other, as in the previously mentioned example

\* *Zeitschrift für physikalische Chemie*, 1902, pp. 40 and 533.

† *Loc. cit.*

‡ *Comptes Rendus*, 1903, pp. 25 and 136; *Ann. Chim. Phys.*, 1902, Series 7, pp. 5 and 26.



of carbon in iron, where the tension was expressed quantitatively by the figure 0.27; and secondly, that certain substances are formed in dilute solid solutions, although, in addition, certain stoichiometric combinations are separated on cooling, just as cementite  $\text{Fe}_3\text{C}$  is deposited in the case of carbon-iron. The chief cause of the hardness of steel consists in the iron being retained either as  $\alpha$ - or  $\beta$ -iron, or else as  $\alpha$ - and  $\beta$ -iron (labile condition below the critical interval). Additional influences on the properties of the steel during sudden cooling can be exerted by prolonged stresses, a result of differences in the contraction of individual strata (cold hardening), which cause deformation of the crystalline structure; and also by the retention of the carbon in a state of solution (in labile equilibrium below  $A_1$ ). This last-named influencing of the properties of steel by sudden cooling is regarded by the author as the most important and effective.



## II.

# THE STRENGTH OF NICKEL-STEEL RIVETED JOINTS,

WITH SPECIAL REFERENCE TO RESISTANCE  
TO SLIP.

BY ERNST PREUSS, DR.ING. (DARMSTADT, GERMANY).

### I. INTRODUCTION.

NICKEL steel was used for the rivets of the Manhattan and Blackwell Island bridges between New York and Brooklyn because of its great strength and other excellent qualities. It was used without extensive tests being made of the strength and other properties of joints riveted with nickel-steel rivets.

The necessity was felt of systematically testing joints riveted with nickel-steel rivets and of ascertaining their ultimate tensile strength, as well as the amount of slip at different loads.

The following is an account of tests made in this respect. Ninety-three nickel-steel riveted joints of all kinds were tested.

The author's thanks are due to a number of people for enabling him to make such extensive tests. In the first place, the Iron and Steel Institute awarded him a Carnegie Research Scholarship. Geheimer Baurat Professor Berndt, director of the Laboratory for Testing Materials at the Technical University of Darmstadt, most generously allowed the staff to give the necessary help, and permitted the use of the machines of the Institute. A number of firms kindly supplied the necessary nickel steel and likewise made the

riveted joints. It was therefore possible to test four different kinds of nickel steel in order to ascertain whether they were suitable for use as rivet material. The different qualities of nickel-steel riveted joints made by hand, hydraulic and electro-hydraulic presses, pneumatic presses, and pneumatic hammers were also tested. The author takes this opportunity of expressing his thanks to the firms and persons mentioned in the footnote.\*

## II. SUMMARY OF THE RESULTS.

The tests lead to the following conclusions: The strength of nickel-steel riveted joints is about two to two-and-a-quarter times as high as that of joints riveted with wrought-iron or mild-steel rivets.

The advantages thus gained are self-evident. For instance, the nodal points in bridge construction are easier to make. As fewer rivets are used, the expenses for rivet material and for making the holes and making the rivets are reduced; while, as rivets of smaller diameter are used, the riveted plates or other parts are less weakened, so that they need not be so broad as they usually are. Though the price of nickel steel is slightly higher than that of other rivet material, this is of no great importance in comparison to the advantages above mentioned; indeed, the higher price of nickel steel is balanced by the smaller amount of the material used.

Of the nickel steel tested only that made in the electric furnace was too brittle to be used. It had an exceedingly high ultimate shearing strength, but this was of little use, as, especially in lap-joints, the brittleness of the nickel steel caused the rivet-heads to break off before the ultimate shearing strength of the rivet-shank had been reached. The

\* Friedrich Krupp, Essen; Bergische Stahlindustrie, G.m.b.H., Remscheid; Röchling'sche Eisen- und Stahlwerke, G.m.b.H., Völklingen a. S.; Dortmunder Brückenbauanstalt C.H. Jucho, Dortmund; Vereinigte Maschinenfabriken, Augsburg and Nürnberg, A.-G.; Zweiganstalt, Brückenbauanstalt, Gustavsburg; Maschinenfabrik, Heinrich Lanz, Mannheim; Frankenthaler Kesselschmiede and Maschinenfabrik, A.-G., Kühnle; Kopp and Kausch, Frankenthal; Maschinenbau-Aktiengesellschaft Pokorný and Wittekind, Frankfurt a./M., Bockenheim.

remaining three kinds of nickel steel were extraordinarily tough, and of the large number of rivets made of these only one rivet-head was broken off, and in this case the rivet was most probably overheated. Further, some heads of rivets of material D, made by the pneumatic hammer, were broken off, but the rivets of this series appear to have been overheated. The heads of other rivets, made of the same material in another shop, did not break off.

The material was so tough that the heads of the rivets, with a shaft diameter of 16 millimetres, were pulled through



FIG. 1.



FIG. 2.

plates of 8 millimetres thickness without receiving any damage, except a slight scraping of the edge of the rivet-head (see Fig. 1). At the same time the rivet-head sheared out the piece of plate lying under it, which is shaded in the accompanying drawing (Fig. 2).

It may be mentioned here that the nickel steel was delivered by the different firms from stock, and was not specially made for riveting purposes. Had the nickel steel been made specially for rivets, still better results than have been reached in these tests might have been attained. This is of especial importance with regard to the electric-nickel steel, for it is in the electric furnace that the qualities of the metal can be so delicately adjusted.

The rivet-heads were of the shape generally used either in boiler-making or in bridge construction, according to

whether the rivets were delivered by boiler-makers or bridge-builders.

With regard to slipping of the plates of a joint, the results of the tests have led the author to other conclusions than those formed by von Bach. The author, who measured the amount of slip with a mirror-reading apparatus, capable of measuring a slip of  $\frac{1}{5000}$  millimetres, found that for nickel-steel riveted joints the slip began asymptotically at loads much smaller than the working load of the riveted joint, whereas von Bach found that no slip took place up to a certain load, but that the plates slipped suddenly when the load was increased by about 1000 kilogrammes. According to von Bach, slip does not take place till the joint is loaded to about 50 per cent. above the working load. Von Bach therefore made the suggestion that the joints should be so designed that the resistance to slipping, and not the resistance to shear, should suffice to withstand the forces acting on the joint.

The author found that the slipping of nickel-steel riveted joints took place before the working load was reached, and the same result was afterwards found with joints riveted with wrought-iron rivets.

The reason for the difference between the author's results and those of von Bach cannot be ascertained, as von Bach makes no statements regarding the manner in which the measurement of his tests was carried out.

With regard to the results obtained by the author, he cannot, therefore, accept von Bach's theory of slipping. In the author's opinion riveted joints should be so designed that the resistance to shearing alone is taken into consideration, as is generally the case.

The slip was found to differ on both sides of the joint, as was likewise the case in von Bach's experiments.

After every load given in the following tables the joint was unloaded, and in every case it was noticed that the plates slipped back to a certain extent. The amounts of elastic and of permanent slip are, therefore, given in the tables of results. By the first is meant the amount of slip while loaded, and by the second the amount which remains after unloading.

Nearly the same amount of slip took place at equal loads with rivets of a large diameter as occurred with those of a smaller diameter. This is probably due to the fact that a larger rivet being intended for a thicker plate, and thicker plates are not so easily pressed together as the thinner ones, the resistance to slip is smaller.

Artificial lengthening of the rivet-shank increases the resistance to slip.

Caulking reduces the slipping, but only to a small extent. Caulking the rivet-heads has a greater effect than caulking the edges of the plates.

This may be caused partly by the fact that, owing to the great strength of the nickel-steel rivets, they had to be placed at a greater distance from the edge of the plate than wrought-iron rivets.

With regard to slip, nickel-steel and wrought-iron rivets were found to be equally efficacious. (See Fig. 5.)

The slipping of butt-joints was greater than that of lap-joints of the same ultimate breaking strength.

The ninety-three joints tested were made by one of the following methods: hand riveting, hydraulic press, electro-hydraulic press, pneumatic press, and pneumatic hammers.

None of the joints made by these different methods showed any distinct advantage with regard to slip; in fact, they seemed in all respects equally good. The slip of the two riveted parts seemed to be less influenced by the manner of riveting than by the state of the two surfaces that came in contact with each other, and by the length of time the snap remained pressed on the rivet-head.

In view of the high shearing resistance of nickel steel it seems advisable to choose, for a given thickness of plate, a rivet with a shank of smaller diameter than is taken for wrought-iron or mild-steel rivets. Otherwise the pitch is apt to be too large, which, in consideration of the caulking and of the resistance to slip, is not advantageous. With thin plates especially it is a good plan to enlarge the rivet-heads to prevent them from being pulled through the plates.

As nickel steel is stronger and harder than the rivet material hitherto used, it requires a greater amount of work



to form it into rivet-heads. In all cases in which the pressure required by the riveting press could be directly measured, it was found to be about 25 per cent. greater than that used for wrought-iron rivets. This cannot be considered a great disadvantage when the extraordinary strength of joints riveted with nickel steel is taken into consideration.

### III. HISTORICAL REVIEW.

Riveted joints are generally designed in such a manner that the resistance to shearing of the whole area of the rivets sheared is equal to the ultimate tensile strength of the weakest section of the parts to be joined. This section is usually the line of the plates weakened by the holes for the rivets. It has, however, been known for a long time that this is not the only force that holds together the two riveted plates or other parts. The other force, which holds together the plates, is the resistance to slipping caused by friction. A rivet is made when hot, in cooling it contracts, and the elastic forces in the direction of its axis, caused by this contraction, press the two parts that are to be joined together. Therefore a movement of the two parts is opposed by the friction between them. The friction varies according to the pressure exerted by the rivets and to the condition of the surface of the parts to be joined. In the following paper this resistance caused by friction will be called resistance to slip. Other things being equal, it is proportional to the total area of the section of all rivets of a joint. In the following,  $G$  represents the resistance to slip for one kilogramme per square centimetre of rivet section. Lavalley\* measured the resistance to slip in riveted joints in the shops of Guin & Co. before the construction of the bridge at Clichy, and found  $G = 1580$  kilogrammes per square centimetre.

In England it was early recognised that there was a resistance to slip in riveted joints. It was pointed out by

\* Molinos and Pronnier, *Traité de la Construction des ponts métalliques*, Paris, 1857; and Köpke, "Versuch einer Theorie der sogenannten Abscherungsfestigkeit und Anwendung derselben auf Brückenträger"; *Zeitschrift des Architekten- und Ingenieur-Vereins für das Königreich Hannover*, vol. iv., 1858, p. 238.



Fairbairn \* in his book, "Britannia and Conway Bridges." †  
 Edwin Clark ‡ describes his experiments with regard to

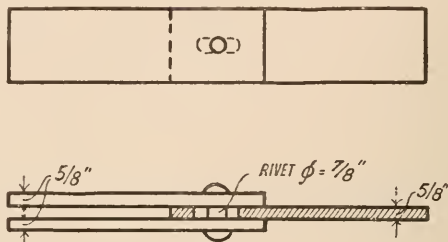


FIG. 3.

the resistance to slip. Three plates of  $\frac{5}{8}$  inch were held together by a  $\frac{7}{8}$ -inch rivet, as in Fig. 3. The hole in the lower plate was oval and larger than the shank of the rivet,

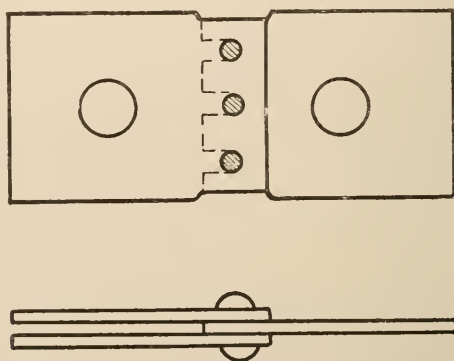


FIG. 4.

so that the rivet did not touch the sides of the hole. There was no slip until the load had reached 5.59 tons. Then a  $\frac{1}{2}$ -inch plate was added on both sides of the joint, so that the length of the rivet, which was still of a diameter of  $\frac{7}{8}$ -inch, was increased by 1 inch. No slip took place until the load was 7.94 tons, because the longer rivet caused an

\* "Useful Information for Engineers," Series I. 5th edition, London, 1874, p. 271.

† London, 1850.

‡ *Polytechnisches Zentralblatt*, 1868, p. 160.

increase in the strain in the direction of the axis of the rivet.

In 1869 Reed published in his book, "Shipbuilding in Iron and Steel," the experiments \* he had made at Pembroke dock on the resistance to slip. The riveted joints were made as in Fig. 4. The middle plate had a slit right to the edge instead of a hole, so that there should be nothing to stop the slipping. Altogether twenty-four joints, of which twelve had wrought-iron plates, were tested and gave the following results :—

TABLE I.

Plates, $\frac{1}{2}$ Inch ; Rivets, $\frac{3}{4}$ Inch.	Resistance to Slipping of 1 Rivet.		
	Test No. 1.	Test No. 2.	Average.
Cup heads . . . .	Tons. 5·14	Tons. 4·21	Tons. 4·67
Pan heads . . . .	5·26	4·81	5·0
Countersunk heads . .	4·56	3·74	4·15

Plates, $\frac{7}{8}$ Inch ; Rivets, 1 Inch.	Resistance to Slipping of 1 Rivet.		
	Test No. 1.	Test No. 2.	Average.
Cup heads . . . .	Tons. 5·84	Tons. 5·61	Tons. 5·7
Pan heads . . . .	6·87	7·24	7·0
Countersunk heads . .	4·56	4·09	4·3

The experiments with mild-steel plates gave somewhat lower values.

In 1883 and 1884 Wildish repeated Reed's experiments at Pembroke dock. He gave an account of the experiments in 1885 before the Institution of Naval Architects.† The riveted joints used by Wildish were also constructed as in Fig. 4.

\* Page 353.

† *Transactions of the Institution of Naval Architects*, 1885, p. 190.

The rivets were of mild steel, partly made by hand and partly by machines. The hand-made rivets gave the following results:—

TABLE II.

Kind of Rivet.	Resistance to Slip of 1 Rivet.	
	1 Inch.	$\frac{3}{4}$ Inch.
	Tons.	Tons.
Cup head . . . . .	6·4	4·72
Pan head . . . . .	7·36	4·52
Pan head . . . . .	8·55	6·25
Countersunk head. . . . .	9·04	4·95

It is peculiar that rivets with countersunk heads gave the greatest resistance to slip. It will be seen later that, theoretically, the opposite result might be expected. The machine-made rivets had cup heads, and the average resistance to slip of rivets with a diameter of 1 inch was 9·6 tons, and of rivets with a diameter of  $\frac{3}{4}$  inch 5·9 tons.

In the discussion of the above-mentioned paper, Kirk announced that years ago he had made experiments to ascertain with what force plates would be pressed together by rivets.

In France Bertin was requested by Considère\* to make experiments on the resistance of plates to slip in the arsenal of Brest. The result was that the maximum resistance to slip was reached by using a riveting heat of 600° C. to 700° C.

In Germany it was early recognised that there was a resistance to slip in riveted joints. Harkort† tested it and found  $G = 1460$  kilogrammes per square centimetre. Schwedler‡ points out in his fundamental work on the strength of rivets, that “the strength of a riveted joint is generally caused by the friction of the two plates against each other.”

\* Considère, *Die Anwendung von Eisen und Stahl bei Konstruktionen*. (German translation by Hauff.) Vienna, 1888, p. 266.

† *Berggeist*, 1861, No. 2.

‡ *Wochenblatt des Architekten-Vereins zu Berlin*, vol. i., 1867, No. 47-49.

Von Kaven\* gave a compilation of the experiments on the resistance to slip up to 1868. Weisbach† likewise treats the subject at length. He was of the opinion that the ultimate strength was equal to the total resistance to slip  $R$  plus the shearing resistance  $S$  of all the rivets, or, when  $P$  is the acting force:  $P = R + S$ . Boehme‡ is of the same opinion. He tested seventeen riveted joints in the Laboratory for Testing Materials at Berlin-Charlottenburg without, however, making special experiments to ascertain the resistance to slip. Th. Landsberg§ shares the same view that  $P = R + S$ . This opinion is, however, untenable. As will be shown later, at small loads the resistance to slip is the only force that holds together the plates, without there being any shearing stress in the rivets. If the forces acting on the joint become greater, then the resistance to slip is overcome, the shank of the rivet comes into contact with the sides of the holes, and then it is only the shearing strength that holds the joint together. When submitted to a high strain lap-joints often gape several millimetres apart, so that for this reason alone there can be no question of a frictional resistance to slip.

About 1890 von Bach|| tested the resistance to slip of over 300 wrought-iron riveted joints. As the account of his experiments is easily procurable, only the principal results will be given here. Von Bach severely criticises the usual method of taking only the shearing strength of rivets into consideration when designing their dimensions. He found that, for well-constructed rivets of ordinary design, the resistance to slip is equal to 1000 to 1500 kilogrammes per square centimetre of rivet section for every pair of surfaces that touch each other. Another of his results was, that the resistance to slip was less influenced by the temperature at which the rivet-heads were formed than by the temperature to which they had cooled down by the time they were finished. For

\* "Collectaneen über einige zum Brückenbau verwendete Materialien," *Zeitschrift des Architekten- und Ingenieur-Vereins zu Hannover*, 1868.

† *Lehrbuch der theoretischen Mechanik*, 1875, p. 557.

‡ *Mitteilungen der Kgl. techn. Versuchsanstalten zu Berlin*, 1883, No. 3.

§ *Zentralbauverwaltung*, vol. v., 1884.

|| *Zeitschrift des Vereins Deutscher Ingenieure*, 1892, p. 1142; *ibid.*, 1894, p. 1231; 1895, p. 301, and *Maschinenelemente*.

instance, a greater resistance to slip was reached by leaving the snap of the riveting machine pressed on the head of the rivet for some time after it was formed, than by removing the snap immediately the rivet was made. This is explained by

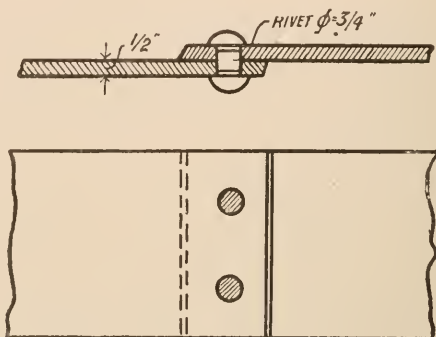


FIG. 5.

the fact that, if the snap is removed too soon, the rivet is still in a soft and non-elastic state, and cannot exert any stress. The longer the shank the greater the resistance to slip, for it is natural that in cooling a long shank exerts the greatest

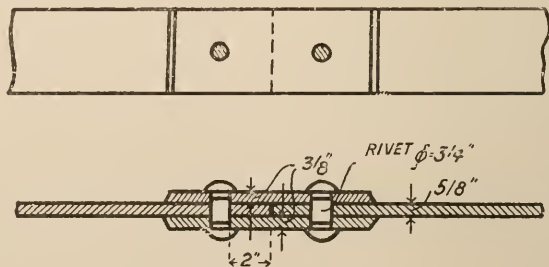


FIG. 6.

stress in the direction of its axis. The resistance to slip in double- or treble-riveted lap-joints must be taken as smaller than in single-riveted lap-joints, because the load to be taken up by the resistance to slip cannot be divided equally among all the rivets. Butt-joints have a smaller resistance to slip than lap-joints.

Caulking, which causes a stress in the direction of the rivet-shank, increases the resistance to slip.

Now that an account has been given of the tests to which wrought iron and mild steel have been put, the nickel-steel riveted joints will be considered. So far no experiments on the resistance to slip of nickel-steel joints have been made, but only those to ascertain their shearing resistance.

After James Riley,\* the originator of the rational use of nickel steel, had pointed out the excellent properties of this material, and these properties had been tested by different authorities, Beardmore † was the first to make some tests with nickel-steel joints. A single-riveted butt-joint of  $\frac{3}{4}$ -inch plates and 6 inches wide, with cover-straps  $\frac{1}{2}$  inch thick, had, on each side of the joint, three  $\frac{3}{4}$ -inch rivets. Its ultimate strength was 82·6 tons. A double-riveted lap-joint of  $\frac{3}{4}$ -inch plates and 6 inches wide, with three  $\frac{3}{4}$ -inch rivets in the first row, and two  $\frac{3}{4}$ -inch rivets in the second, had an ultimate strength of 69·8 tons.

TABLE III.

Heat of the Rivet.	Breaking Load, Kilogrammes.	Ultimate Shearing Strength, Kilogrammes per Square Centimetre.	Manner of Fracture.
<i>Series I.</i>			
Light cherry-red .	38,400	6720	Rivet-hole sheared out.
Light red . . .	39,600	6920	Rivets sheared.
Yellow . . . .	36,500	6380	Rivets sheared.
Nearly white . .	35,500	6220	Rivets sheared.
Light cherry-red .	32,000	5590	Head of rivets broken off.
Light red . . .	38,800	6770	Rivet-hole sheared out.
Yellow . . . .	41,100	7180	Head of rivets broken off.
Nearly white . .	36,100	6320	Head of rivets broken off.
<i>Series II.</i>			
Light red . . .	35,500	6200	Rivet hole sheared out.
Light red . . .	36,800	6440	Rivets sheared.
Light yellow . .	37,800	6610	Rivet-hole sheared out.
Light yellow . .	33,500	5860	Rivets sheared.
Light red . . .	38,000	6640	Rivet-hole sheared out.
Light red . . .	37,300	6520	Rivet-hole sheared out.
Light yellow . .	36,000	6290	Rivet-hole sheared out.
Light yellow . .	38,000	6640	Rivet-hole sheared out.

\* "Alloys of Nickel and Steel," *Journal of the Iron and Steel Institute*, 1889, No. I. p. 45.

† "On Nickel Steel," *Transactions of the Institution of Engineers and Shipbuilders in Scotland*, vol. xxxix., 1895, p. 229; and *Industries and Iron*, May 1, 1896.



Extensive tests of nickel-steel riveted joints were made by Maunsel White,\* the testing engineer for the Bethlehem Steel Co. The rivets used by White had a shank of  $\frac{3}{4}$ -inch diameter. His first series of experiments was carried out as in Fig. 5, and the second series as in Fig. 6. The heat of the rivets varied from light cherry-red to nearly white, and the results obtained are given in Table III. (p. 71).

White made control tests in the same manner with the usual rivet material. These gave the following results:—

Riveted Joint, according to Figure. No.	Breaking Load, Kilogrammes.	Ultimate Shearing Strength, Kilogrammes per Square Centimetre.
5	24,100	4220
6	25,000	4380

#### IV. QUALITY REQUIRED IN THE MATERIAL USED FOR RIVETS.

It is most important that rivet material should have a high ultimate shearing strength. A high ultimate tensile strength and yield-point are likewise desirable, so that in cooling the contraction should not cause the rivet to break or to stretch, as it would render impossible a stress in the direction of the rivet-shank, and there would, therefore, be no resistance to slipping. The second requisite is that the yield-point should also be high at high temperatures. Above the yield-point the material is, so to say, in almost a non-elastic and doughy state. Therefore elastic stresses in the rivet-shank and the resultant resistance to slip cannot take place until the material has cooled down below the yield-point.

For instance, if two materials are taken, of which the first has a certain value for its yield-point at a temperature of  $400^{\circ}$  C., and the second has the same value for its yield-point

\* "Nickel Steel Rivets," *Journal of the American Society of Naval Engineers*, 1898, vol. x., p. 1038; and Browne, "Nickel Steel, A Synopsis of Experiment and Opinion," *Transactions of the American Institute of Mining Engineers*, vol. xxix., 1899, p. 569.

at a temperature of  $500^{\circ}$  C., the elastic stresses caused by contraction of the rivet-shank by cooling will begin in the first case at  $400^{\circ}$ , whereas in the second case it will begin at  $500^{\circ}$ . Given an equal coefficient of expansion by heat the contraction in the second case will be one and a quarter times as great as in the first case. For this reason the author has made exhaustive tests as to the ultimate strength and the yield-point of the rivet material. The results are given later.

It is further required that the material for rivets should not be hard and brittle, but, to a certain extent, soft and tough. This is necessary in order to prevent the rivet-heads breaking off, and to avoid the riveting machines having to exert a greater pressure than has hitherto been used in making mild-steel rivets. With a harder material the effect of caulking would not be so good, as the workman is used to exerting a certain amount of energy for this work, which can scarcely be exceeded for practical reasons.

White's experiments show that a greater force is needed to form the rivet-heads than is used in making soft-steel rivets. The heads never broke off in his experiments.

It is likewise advantageous to be able to rivet at a low temperature. Ellis\* made tests like those carried out by Souther and Flavel, and found that the best temperature for riveting with nickel steel is cherry-red heat. Occasional overheating of the rivets should not injure their material. The author has therefore made tests in this direction.

As the resistance to slip depends on the contraction of the rivet-shank when cooling, a material with the largest coefficient of expansion by heat will be the best. According to Guillaume,† director of the International Bureau of Weights and Measures at Paris, there is practically no difference between the coefficients of expansion of carbon steel and nickel steel containing up to 5 per cent. nickel. In this respect, then, the two materials are equally good.

As the rivets have to stand changes of stress, the effect of fatigue tests on them must be taken into consideration.

\* "Recent Experiments in Armour," *Transactions of the Institution of Naval Architects*, March, 1894.

† "Recherches sur les Aciers au Nickel," *Comptes Rendus*, March 7, 1898.

Beardmore\* has made tests in this respect. He subjected carbon steel and nickel steel to the same fatigue test, and found the latter to be much superior.

Landis† made similar tests with the same results. Against shock, nickel steel has more resistance than carbon steel. According to Wiggin‡ nickel steel withstands impact even better than is to be expected from the ratio of the ultimate tensile strength of nickel steel to that of carbon steel.

It is further of importance that the rivet material should be homogeneous, and that there should be no segregation in the middle of the billet. Porter tested this with nickel steel billets at the Bethlehem Steel Works. He used a billet with a diameter of 60 centimetres and a length of 200 centimetres. He found the following distribution of the different elements:—

	On the Surface.	15 Centimetres from the Central Axis.	Ratio of Concentration.
	Per Cent.	Per Cent.	
Nickel . . . . .	3·07	3·27	100 : 108
Silicon . . . . .	0·172	0·170	100 : 98
Sulphur . . . . .	0·03	0·06	100 : 200
Carbon . . . . .	0·31	0·36	100 : 116
Phosphorus . . . . .	0·025	0·047	100 : 188

Of great importance to rivet material is the manner in which it resists the influence of corrosion by water, especially by salt water. White§ left wrought-iron and nickel-steel rivets for twelve months in salt water in Leith harbour, and found the following reductions in weight:—

Material.	Reduction in Weight.
	Per Cent.
Finished nickel steel with 3 per cent. nickel . . . . .	1·36
Finished wrought iron . . . . .	1·89
Unfinished nickel steel . . . . .	0·74

\* *Transactions of the Institution of Shipbuilders of Scotland*, 1895-1896, p. 229.

† *Scientific American*, January 9, 1897.

‡ "Nickel Steel," *Journal of the Iron and Steel Institute*, 1895, No. II. p. 164.

§ See Beardmore, "Nickel Steel as an Improved Material for Boiler Plates."

Wiggin gives the following results :—

Material.	Reduction in Weight after Three Months' Boiling in a 10 per Cent. Salt Solution.	Reduction in Weight after Exposure to Steam for Two Months.
	Per Cent.	Per Cent.
Nickel steel containing 3 per cent. nickel . . . . .	1.00	0.27
Bessemer steel . . . . .	1.81	0.58
Open-hearth steel . . . . .	1.97 - 2.00	0.31 - 0.36

According to Howe, the reduction in weight per square centimetre of surface when the iron is left in water is as follows :—

Material.	Salt Water.	Fresh Water.
	Per Cent.	Per Cent.
Wrought iron . . . . .	0.000069	0.000062
Mild steel with low carbon percentage . . . . .	0.000078	0.000059
Nickel steel with low nickel percentage . . . . .	0.000057	0.000050
Nickel steel with high nickel percentage . . . . .	0.000022	0.000021

It is further desirable that there should not be a great difference of electric potential between the nickel-steel rivets and the wrought-iron or mild-steel plates, in order to avoid destruction by electrolytic corrosion. The author therefore made experiments in this direction, which will be described later.

## V. THE PROPERTIES OF THE MATERIAL USED IN THE FOLLOWING TESTS.

In the printed specifications and estimates for the Manhattan Bridge, New York,\* is found practically all that is known about the chemical composition of nickel steel for rivets. These specify—

	Per Cent.
Lowest percentage of nickel . . . . .	3.25
Highest percentage of phosphorus . . . . .	0.035
"    "    of sulphur . . . . .	0.03
"    "    of manganese . . . . .	0.60
"    "    of silicon . . . . .	0.10

\* "Proposals for Bids or Estimates for the Manhattan Bridge." New York, 1906.

Further, it is specified that the ultimate tensile strength must be 49 to 56 kilogrammes per square millimetre, and the elastic limit 32 kilogrammes per square millimetre. According to the ultimate strength the material must have an elongation of 20 to 26 per cent. on a length of 8 inches. When cold it must stand bending through an angle of  $180^\circ$  without cracking.

The firms who supplied the materials for the following tests stated that the materials had the following chemical composition:—

Material No.	Composition.					
	Nickel.	Chromium.	Carbon.	Man-ganese.	Phos-phorus.	Sulphur.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
A . . .	4.0	1.0	0.1	0.35	...	...
B . . .	3.2	...	0.15	0.8	0.01	0.03
C . . .	3.4	...	0.36	0.29	0.01	0.02
D . . .	3.2	...	0.15	0.6	...	...

Round test specimens with the diameter  $d$  were tested in a double-shearing apparatus, and found to have the following ultimate shearing strength:—

Material No.	Test No.	Diameter, Millimetres.	Ultimate Strength, Kilogrammes.	Shearing Strength, Kilogrammes per Square Millimetres.
A	1	...	23.300	82.2
	2	19.0	23.200	81.8
	3	...	23.100	81.4
				average: 81.8
B	1	...	21.400	76.8
	2	18.85	20.700	74.3
	3	...	20.600	74.0
				average: 75.0
C	1	...	28.000	99.6
	2	18.9	27.700	98.5
	3	...	28.300	100.7
				average: 99.6
D	1	...	22.800	82.7
	2	18.8	22.800	82.7
	3	...	22.800	82.7
				average: 82.7

The tenacity was first tested at  $+ 20^\circ \text{C.}$ , and gave the results shown in Tables IV. and V.

TABLE IV.—*Tensile Tests. A. Temperature, 20° C. Round Test Specimens of 11 Millimetres Diameter.*

Material No.	Test No.	Diameter. Millimetres.	Section. Square Millimetres.	Elastic Limit.		Yield-Point.		Ultimate Strength.		Elongation on 110 Millimetres per Cent.	Contraction per Cent.
				Kilogrammes.	Kilogrammes per Square Millimetre.	Kilogrammes.	Kilogrammes per Square Millimetre.	Kilogrammes.	Kilogrammes per Square Millimetre.		
A	1	11.00	95.0	3200	33.7	4450	46.8	5250	55.3	20.2	79.3
	2	10.95	94.1	3200	34.0	4470	47.5	5320	56.5	20.2	78.3
B	1	10.90	93.3	2800	30.0	3100	36.4	4780	51.2	24.2	64.0
	2	10.95	94.1	2900	30.8	3380	35.9	4820	51.2	23.4	64.0
C	1	11.00	95.0	2600	27.4	* ...	...	7450	78.4	16.6	44.3
	2	11.00	95.0	2900	30.5	* ...	...	7500	78.8	16.4	44.3
D	1	11.00	95.0	2900	30.5	3600	37.9	4970	52.3	27.2	62.8
	2	11.00	95.0	2900	30.5	3600	37.9	4930	51.9	25.4	62.8

\* Yield-point not marked.



TABLE V.—*Tensile Tests. B. Temperature, 20° to 600° C. Round Test Specimens of 10 Millimetres Diameter. Material D.*

Heat. Degrees Centigrade.	Test No.	Diameter. Millimetres.	Section. Square Milli- metres.	Yield-Point.		Ultimate Strength.		Elongation on 110 Millimetres per Cent.	Contraction per Cent.
				Kilogrammes.	Kilogrammes per Square Millimetre.	Kilogrammes.	Kilogrammes per Square Millimetre.		
20	{	11.00	95.0	3600	37.9	4970	52.3	27.2	62.8
		11.00	95.0	3600	37.9	4930	51.9	25.4	62.8
100	{	9.9	77.0	3200	41.6	4190	54.4	21.4	66.8
		9.95	77.6	3200	41.2	4220	54.4	21.6	67.0
200	{	10.0	78.6	3000	38.2	4160	52.9	20.6	68.5
		9.8	75.4	2900	38.5	4090	54.2	19.6	66.2
300	{	10.0	78.6	2600	33.1	4245	54.0	15.3	66.7
		10.0	78.6	2600	33.1	4180	53.2	...	63.0
400	{	10.0	78.6	2200	28.0	3660	46.6	20.0	78.2
		10.0	78.6	2200	28.0	3800	48.3	20.5	78.2
500	{	10.0	78.6	1350	17.2	2100	26.7	25.9	79.2
		9.9	77.0	1200	15.6	1720	22.3	29.2	82.0
600	{	10.0	78.6	850	10.8	1090	13.9	34.4	93.0
		9.85	76.2	850	11.2	1220	16.0	37.0	92.6

The values obtained for the ultimate tensile strength, the yield-point, and the elongation at high temperatures are graphically represented in Fig. 7. In the same diagram the values found by Rudeloff\* for wrought iron at high temperatures are also given. The diagram shows that at high temperatures the ultimate strength of nickel steel is greater than that of wrought

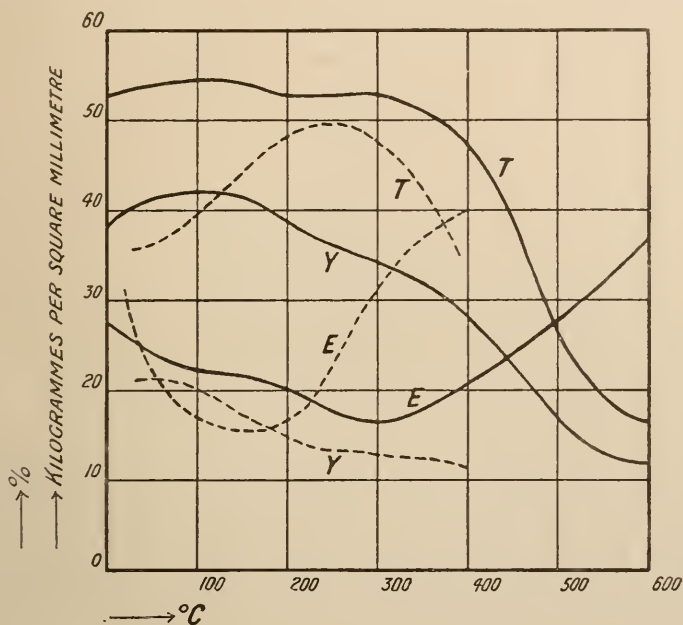


FIG. 7.

— Nickel steel.    - - - - - Wrought iron.    T, tensile strength.  
Y, yield-point.    E, elongation.

iron, and likewise that at high temperatures the yield-point of nickel steel is materially higher than that of wrought iron at the same temperature. The latter fact is of great importance, because after the rivet has been made and is cooling down, no pressure can be exerted by the rivet in the direction of its axis until the yield-point has been passed—that is, until

\* *Mitteilungen aus dem Kgl. Techn. Versuchsanstalten zu Berlin*, 1893, p. 327.

the rivet has passed from a doughy state to a state of elasticity.

In order to ascertain whether nickel steel becomes brittle by being heated to a high temperature, impact tests were made with notched specimens according to Heyn's method.\* Short bars of 60 millimetres in length, with a section of  $4 \times 6$  millimetres, were made with a notch  $\frac{1}{2}$  millimetre deep in the middle. These bars were fixed into a vice with sharp-edged jaws, with the notch at the top edge of the jaws, as

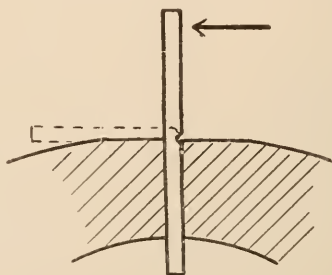


FIG. 8.

shown in Fig. 8. The top half was then bent  $90^\circ$  by hitting it with a hammer, and then bent backward and forward.

Every time it was bent from the normal position to a right angle or back again counted as one bending. The values in Table VI. are the results of tests with the material A.

The test specimens were kept for half-an-hour at the temperature given in the table, and then slowly cooled down. It will be seen that the material becomes less tough by being highly heated. Even after being made white hot the number of bends was  $1\frac{3}{4}$ , which is a good value for boiler plates. The number of bends becomes larger again when the specimens are very highly heated.

It has already been mentioned previously that the electric potential between the rivets and the plates to be joined together should not be too high, in order that the materials should not suffer corrosion by electrolysis. To determine

\* *Mitteilungen aus dem Kgl. Materialprüfungsamt zu Gross-Lichterfelde West*, 1906, p. 263.

the influence of electrolytic action six nickel-steel rivets and six wrought-iron rivets were riveted into two mild-steel

TABLE VI.

$\frac{1}{2}$ Hour heated at Degrees Centigrade.	Test No.	Number of Bends.
As delivered	$\begin{cases} 1 \\ 2 \\ 3 \end{cases}$	$\begin{matrix} 3\frac{1}{2} \\ 3\frac{1}{2} \\ 3\frac{1}{2} \end{matrix}$
640	$\begin{cases} 1 \\ 2 \\ 3 \end{cases}$	$\begin{matrix} 3\frac{3}{4} \\ 3\frac{3}{4} \\ 3\frac{3}{4} \end{matrix}$
740	$\begin{cases} 1 \\ 2 \\ 3 \end{cases}$	$\begin{matrix} 2 \\ 2 \\ 1\frac{3}{4} \end{matrix}$
840	$\begin{cases} 1 \\ 2 \\ 3 \end{cases}$	$\begin{matrix} 1\frac{3}{4} \\ 1\frac{3}{4} \\ 2 \end{matrix}$
940	$\begin{cases} 1 \\ 2 \\ 3 \end{cases}$	$\begin{matrix} 1\frac{3}{4} \\ 1\frac{3}{4} \\ 1\frac{3}{4} \end{matrix}$
1040	$\begin{cases} 1 \\ 2 \\ 3 \end{cases}$	$\begin{matrix} 2\frac{1}{2} \\ 2\frac{1}{2} \\ 2\frac{1}{2} \end{matrix}$

plates, which were then left for two months in salt water without any protective coating.

The percentage of salt in the water was about that of sea water, namely, 3·6 per cent. The following reductions in weight took place in the two months during which the tests lasted :—

Material.	Weight at beginning of Test.	Loss of Weight during the Test.
	Grammes.	Grammes.
Mild-steel plate with nickel-steel rivets . .	2567	11
Mild-steel plate with wrought-iron rivets . .	2794	6

The electric potential between mild steel and wrought iron and between mild steel and nickel steel was directly measured.

These tests were carried out by Punga, in the Electro-Technical Institute of the Technical University of Darmstadt, who reported as follows:—

The electrodes were flat and their upper surface was covered with wax, which came slightly below the surface of the liquid when the electrodes were immersed. The jars were placed where they would not be shaken, as the slightest disturbance has an influence on the electric potential. The electrodes were rubbed with emery paper and with rag before being put into the liquid. The measurements were made by the compensation method.\* Trial experiments showed that the electric potential was more or less influenced by factors over which little or no control could be exercised. The values given must therefore be regarded as comparative, and not as absolute values.

TABLE VII.—*Test No. 1. Water from the Town Supply.*

No.	Time.		E <sub>1</sub> Nickel Steel.	E <sub>2</sub> Wrought Iron.	E <sub>1</sub> /E <sub>2</sub> .
	Hrs.	Mns.	Volt.	Volt.	
1	0	6	0·1385	0·0729	1·90
2	0	20	0·1520	0·0496	3·06
3	1	0	0·1250	0·0322	3·88
4	4	0	0·0616	0·0146	4·22
5	7	0	0·0536	0·0173	3·10
6	22	0	0·0473	0·00770	6·14
7	28	0	0·0428	0·00382	11·20

*Test No. 2. Dilution of 3·6 per Cent. Salt in Water.*

No.	Time.		E <sub>1</sub> Nickel Steel.	E <sub>2</sub> Wrought Iron.	E <sub>1</sub> /E <sub>2</sub> .
	Hrs.	Mns.	Volt.	Volt.	
1	0	6	0·0645	0·0514	1·25
2	0	25	0·0344	0·0434	0·73
3	1	0	0·0392	0·0344	1·11
4	4	0	0·0429	0·00943	4·44
5	7	0	0·0523	0·00723	7·24
6	22	0	0·0383	0·00937	4·07
7	28	0	0·0380	0·01045	3·64

\* *Mitteilungen aus dem Kgl. Materialprüfungsamt zu Gross-Lichterfelde West*, 1908, Heft 1 and 2, p. 50.

Table VII. gives the electric potential between nickel steel and wrought iron, on the one hand, and mild steel on the other as a function of the time, beginning at the moment of the plunging in of the electrodes. As the electric potential at first varied constantly, it could not be compensated, therefore the first reading was made six minutes after submerging the electrodes. The ratios of the electric potentials to each other are likewise inserted in the table.

The temperature was on an average  $16^{\circ}$  C. As the potential of mild steel is always a minus quantity, the signs have not been given in the tables.

The results of the tests, therefore, show that the electric potential between nickel steel and mild steel is higher than that between wrought iron and mild steel when submerged in the liquids used. The ratio  $E_1 : E_2$  varies materially with the time.

## VI. MEASURING APPARATUS.

All the riveted joints were tested in Werder's testing-machine, which was arranged as shown in Fig. 9. It was originally intended to fix the riveted joints into the testing-machine by two bolts, one of which passed through a hole in each end of the joint, shown in Fig. 10, exactly as it was done by von Bach in his experiments. This method of fixing the joint has the advantage that the forces act in the axis of the joint. The great strength of the joints riveted by nickel-steel rivets, however, caused too great a pressure in the surface of the holes. For this reason the joints that did not exceed a breadth of 200 millimetres were fixed with wedges into a grip. As all the results of the different tests in one series are very nearly the same, it is evident that the wedges have acted quite as effectively as the bolts would have done. As the grip held only plates up to 200 millimetres in breadth, the broader ones had to be fixed by bolts; but to reduce the pressure in the holes the two ends of the joints were made thicker by riveting a plate on to each side.

Before choosing the instrument for measuring the amount



of slip, the question as to the degree of exactitude necessary had to be decided.



FIG. 9.

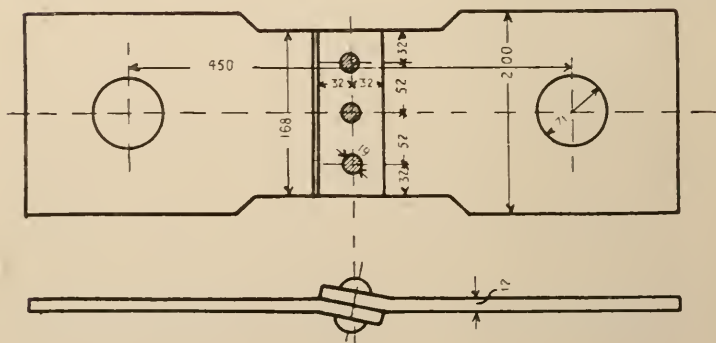


FIG. 10.

In view of von Bach's tests, and for other reasons, it was deemed desirable to be able to measure  $\frac{1}{100}$  millimetre. It is quite possible to measure  $\frac{1}{100}$  millimetre by mechanical

instruments, but as it was of great importance to ascertain when the slipping commenced, which, as already pointed out, can be said, for practical considerations, to take place when the plates have changed their position by about  $\frac{1}{100}$  millimetre, it was not thought advisable to choose mechanical apparatus for measuring such a small length as  $\frac{1}{100}$  millimetre, as it is just at the beginning of the movement that such mechanical instruments, for various reasons, do not give exact results.

For the purpose of measuring the slip, therefore, a mirror-reading apparatus in conjunction with a Martens' knife-edge was used. The ratio chosen was 1:500,\* so that a slipping of the plates to the extent of  $\frac{1}{100}$  millimetre was represented on the scale by 5 millimetres. As  $\frac{1}{10}$  millimetre can be estimated correctly on the scale, a slipping of the plates to the extent of  $\frac{1}{5000}$  millimetre could be measured. This degree of exactitude being greater than was required, the slip is always given in the results with a unit of  $\frac{1}{100}$  millimetre.

In order to control this method the side-edges of the riveted plates were in some cases polished, and had lines scratched very near together on them, so that the slip could be measured with a unit of  $\frac{1}{100}$  millimetre with the aid of a micrometer and magnifying-glass. The results found by the two methods were very nearly the same, and as the mirror readings were much more quickly made, and were more exact, they were in the end used alone.

The slip was always measured at both sides of the joints, and the average of these two values is given in the following tables. The slip was found to differ on the two sides of the joint, as was shown in the tests made by von Bach.

To measure the slipping of lap-joints the arrangement No. 1 (see Fig. 11) was used. Two screws, P and R, were fixed into the edge of each plate. Between the head of the screw P and a tube the spring F was fastened, and between the spring and the head of the screw R the knife-edge S was placed. The mirror M is fastened to the knife-edge S by the pin D.

This arrangement was abandoned later on for two reasons. To begin with, the instrument used afterwards was simpler,

\* In some of the first tests = 1 : 550.

and, further, the objection to the first arrangement was that the slip was not measured in the plane in which it took

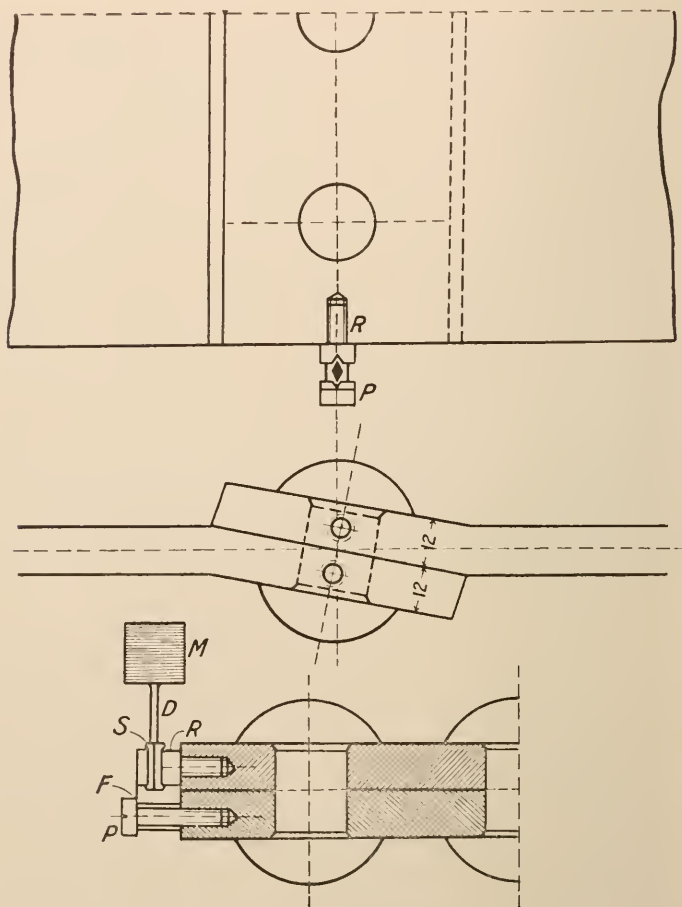


FIG. 11.—No. 1 Apparatus for Measuring the Slip of Riveted Joints.

place, and that the elongation of the plates caused by shearing stresses might affect the results.

For the arrangement No. 2 (Fig. 12) a hole of 4 millimetres in diameter and 10 millimetres in length was bored in the middle of line of contact of the two plates of the joint. The Martens'

knife-edge of 4.24 millimetres in breadth was driven into this hole by tapping it lightly with a hammer, so that it was firmly fixed. The mirror *M* was joined to the knife-edge by

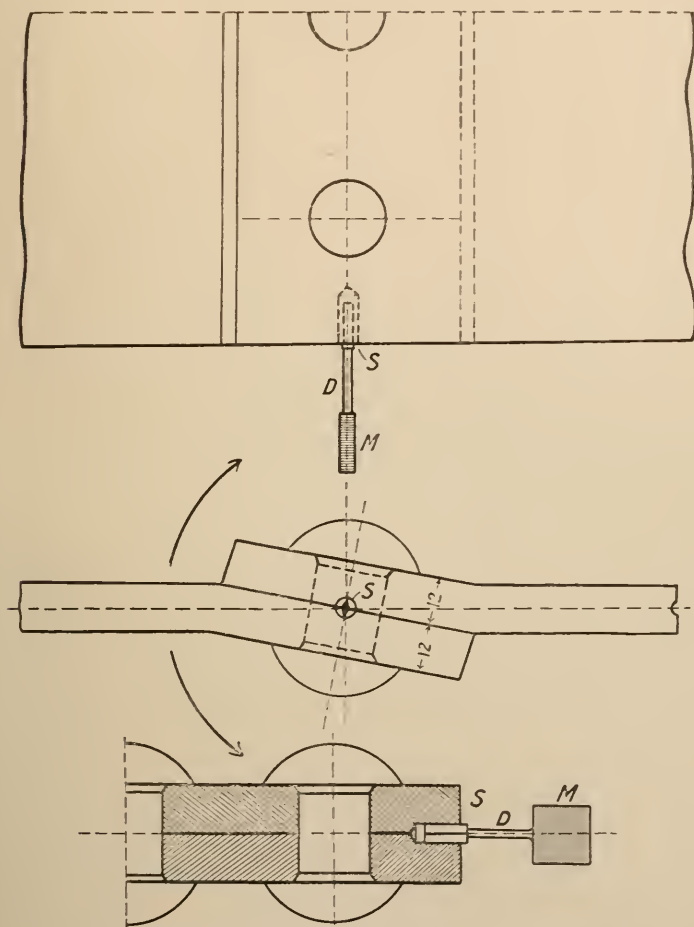


FIG. 12.—No. 2 Apparatus for Measuring the Slip of Riveted Joints.

the pin *D*. This arrangement still had a disadvantage, namely, that if the point of section of the central lines of the plates and of the rivets does not coincide with the centre of the line of contact of the two plates, a moment tending to turn the over-

lapped part of the joint in one or other of the directions shown by the arrows in the figure is created. As there is no certainty

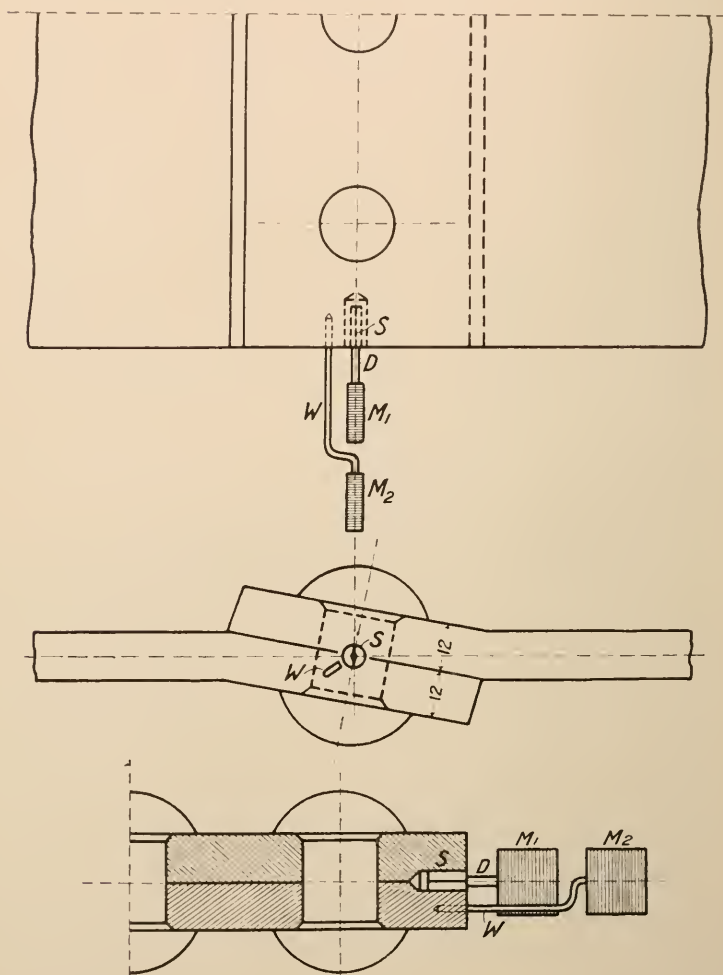


FIG. 13.—No. 3 Apparatus for Measuring the Slip of Riveted Joints.

that the above-mentioned condition is fulfilled, that the central lines bisect each other in the centre of the lap-joint, a slight movement of this point of the lap-joint has to be taken into

consideration, and must therefore be measured. To attain this object some improvements were made in the arrangement No. 2.

In the arrangement No. 3 (Fig. 13) a second mirror  $M_2$ , which lay exactly in the same plane as the mirror  $M_1$ , was fastened

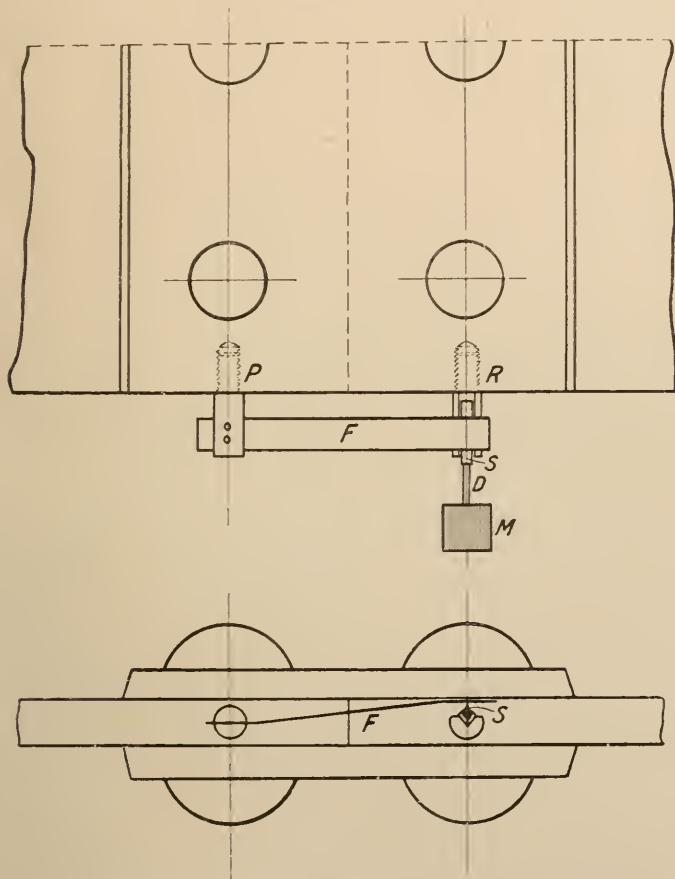


FIG. 14.—No. 4 Apparatus for Measuring the Slip of Riveted Joints.

to a bent wire  $W$ . The movement of the centre of the lap-joint could, therefore, be measured and taken into consideration by means of this mirror  $M_2$ . The results show that this movement is very slight.

The arrangement No. 4 (Fig. 14) was used to measure the slip



in butt-joints. Into both the plates screws P and R were fixed. A spring F was fastened to the screw R, and the head of screw R was notched. The Martens' knife-edge was fixed between this notch and the spring F, and the mirror was again fastened to the knife-edge by a pin. As shown in the figure, the screws P and R were placed at the same distance from the edge of the plates as the rivets, in order to avoid the results being influenced by the elongation of the plates.

## VII. EXPERIMENTS OF THE AUTHOR.

Altogether ninety-three riveted joints were tested. The design of the riveted joints was, as nearly as possible, like those used by von Bach in his extensive tests with wrought-iron rivets, so that a comparison between nickel-steel and wrought-iron rivets might be made.

In the results of his experiments von Bach as a rule gives only the load at which the slip in the riveted joint commenced. In the present paper the amount of slip is given for a series of loads, gradually increasing in weight. The amount of slip which is permanent after the load has been removed has been given in addition to the elastic slip when under load, as it was observed that the plates, after being unloaded, did not remain in the relative position they had taken up while loaded, but slipped back considerably. After being heavily loaded the slipping backwards of the plates could easily be seen with the naked eye.

In the tables of results of the tests the loads at which the slipping commenced are given as far as possible according to von Bach's tests. It may be here remarked, and this point will be more extensively treated later, that according to von Bach the slipping takes place suddenly at a certain load, while the author's results prove that the slipping begins gradually and asymptotically, as is shown by the apparatus, which measures a slip of  $\frac{1}{5000}$  millimetre.

All the riveted joints were loaded to their ultimate strength, as the author is of opinion that the resistance to slip plays only a very secondary part in comparison to the ultimate shearing strength of the riveted joint.

In the report of the results of these tests, the values found by von Bach for the ultimate strength of wrought-iron riveted joints with the same rivet diameter and with the same number of rivets, &c., are given for the sake of comparison. As von Bach gives the ultimate strength only in a few cases, in all other cases the ultimate strength is given as found by calculation when the joint has the same number of rivets of the same diameter and a rivet material with a shearing strength of 35 kilogrammes per square millimetre.

All holes for the rivets were drilled. All the joints were so designed that the ultimate shearing strength of the area of rivets sheared was equal to the ultimate tensile strength of the plates at the section which was most weakened by the rivet-holes. The ultimate shearing strength of the nickel steel for this calculation was taken as 80 kilogrammes per square millimetre. As has already been stated, the ultimate shearing strength of the nickel steel lies between 80 and 100 kilogrammes per square millimetre. Forty kilogrammes per square millimetre was taken as the ultimate tensile strength of the plates.

The distance of the rivets from the edge of the plate was calculated in the usual way, so that the force necessary to shear the hole to the edge of the plate is equal to the load acting on the rivet. The result of these conditions naturally was that the pitch and the distance of the rivets from the edge of the plates were much greater than usual, especially as the diameter of the rivets, in respect to the thickness of the plates, was the same as is generally taken for ordinary rivet material. This does not have any bad effect on the strength of the joint, except the one shown in Fig. 16, where the pitch was evidently too great, as the rivet-heads were pulled through the plates. But in order to get a good tight joint the pitch and distance of the rivets from the edge of the plate must not be too great. It would appear to be impossible to make laboratory tests as to the pitch and the distance of the rivets from the edge of the plates which give the best and most durable tight joints. This point can be decided only by long practical experience.

It is therefore advisable not to exceed the rivet pitch and

distance from the edge of the plates that are generally used for a given thickness of plate, but in consideration of the greater strength of the nickel-steel rivets to choose a smaller diameter.

The following tables (VIII. and IX.) show the varieties of riveted joints that were tested:—

TABLE VIII.—I. *Lap-joints.*

	As in Figure No.	Series.	Number of Tests.
<i>A.—Single-riveted Lap-joints.</i>			
1. Diameter of rivet, 16 millimetres; thickness of plates, 8 millimetres; not caulked; made by—			
(a) Electro-hydraulic press . . . . .	16	Ia	5
(b) Hydraulic press . . . . .	16	Ib	3
(c) Pneumatic hammers . . . . .	16	Ic	3
(d) Hand . . . . .	16	Id	3
2. Diameter of rivet, 19 millimetres; thickness of plates, 12 millimetres.			
(a) Not caulked; made by—			
(aa) Electro-hydraulic press . . . . .	33	IIa	5
(bb) Hydraulic press . . . . .	33	IIb	3
(cc) Pneumatic hammers—			
(aaa) Riveting heat cherry-red . . . . .	35	IIc	3
(bbb) Riveting heat light red . . . . .	35	IIId	3
(b) Heads of rivets caulked; plates not caulked; made by—			
Electro-hydraulic press . . . . .	35	III	5
(c) Heads of rivets not caulked; plates caulked; made by—			
Electro-hydraulic press . . . . .	35	IV	5
(d) Heads of rivets and plates caulked; made by—			
(aa) Electro-hydraulic press . . . . .	33	Va	5
(bb) Hydraulic press . . . . .	33	Vb	3
(cc) Pneumatic hammers . . . . .	35	Vc	3
(e) Tests with wrought-iron rivets for comparison; made by—			
(aa) Electro-hydraulic press . . . . .	...	VIIa	5
(bb) Hydraulic press . . . . .	...	VIIb	3
(f) Rivets with shanks lengthened by straps; not caulked; made by—			
Electro-hydraulic press . . . . .	38	VI	5
3. Diameter of rivet, 25 millimetres; thickness of plates, 18 millimetres; not caulked; made by—			
(a) Electro-hydraulic press . . . . .	40	VIIIa	5
(b) Hydraulic press . . . . .	40	VIIIb	3
(c) Pneumatic press . . . . .	40	VIIIc	3
<i>B.—Double-riveted Lap-joints.</i>			
Diameter of rivet, 19 millimetres; thickness of plates, 12 millimetres; not caulked; made by—			
Electro-hydraulic press . . . . .	42	IX	5

TABLE IX.—II. *Butt-joints.*

Single-row Butt-joint, not Caulked.	As in Figure No.	Series.	Number of Tests.
A. Diameter of rivet, 16 millimetres; thickness of plates, 8 millimetres; made by—			
(a) Hydraulic press . . . . .	43	Xa	3
(b) Pneumatic hammers . . . . .	43	Xb	3
(c) Hand . . . . .	43	Xc	3
B. Diameter of rivet, 19 millimetres; thickness of plates, 12 millimetres; made by—			
(a) Hydraulic press . . . . .	44	X1a	3
(b) Pneumatic hammers . . . . .	44	X1b	3

In Table X. are shown the results of the test as made for every joint:—

This table is particularly intended to show that the lap-joints scarcely turned when loaded in the testing-machine. This turning can be measured by the mirror  $M_2$ , see page 88. The reading of the mirror  $M_2$  is represented in exactly the same way as the slipping of the two plates, measured by the reading of mirror  $M_1$ .

Therefore the readings obtained through the mirror  $M_2$  were likewise given with a unit of 0.01 millimetre, which is really incorrect, but the values obtained by the mirror  $M_1$  are by this means more easily corrected.

The table also shows that the values for the slip measured with the mirror-reading arrangement and with the aid of a micrometer and the relative change of position of lines scratched on the edges of the joint, correspond very well with each other. It may be here remarked that measuring with the micrometer is less exact than the mirror-reading method, as the scratched lines have a much greater breadth than  $\frac{1}{5000}$  millimetre.

It has already been stated on page 63 of the summary of results, that, according to the author's experiments, the slip begins gradually and asymptotically, and that there can therefore be no question of a sudden beginning of the slipping, as given in von Bach's tables of results.

Table X., giving results of test No. 14, illustrates this point very clearly.

TABLE X.—*Test No. 14. A. Nickel-Steel Riveted Joints.*

Date, 30.9.08.

Kind of nickel steel, A.

Maker, F.

Manner of riveting, hydraulic press.

Series, No. Vh.

Drawing, 2.

Ultimate strength, 49,020 kilogrammes.

Ratio of Mirror-reading apparatus, 1 : 550.

Lap-joint.

Caulked.

Single lap-joint.

Number of rivets, 3.

Diameter of rivets, 19 millimetres.

Riveting heat, light red.

Thickness of plate, 12 millimetres.

Snap on head of rivet, normal.

*Results.*

Load, Tons.	Reading 0.002 Millimetre.			Slip in 0.01 Millimetre.						Twist, measured by Mirror M <sub>2</sub> 0.01 milli- metre.
	Mirror M <sub>1</sub> .		Mirror. M <sub>2</sub>	Above.		Below.		Average.		
	Above.	Below.		Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
1	315	269	315	0	...	0	...	0	...	0
2	317	271	317	0	...	0	...	0	...	0
3	318	273	317	0	...	0	...	0	...	0
4	319	273	318	0	...	0	...	0	...	1
5	319	274	318	0	...	0	...	0	...	1
6	320	275	319	0	...	0	...	0	...	1
7	320	276	319	0	...	0	...	0	...	1
8	321	276	319	0	...	0	...	0	...	1
10	322	278	320	0	...	0	...	0	...	1
12	323	280	320	0	...	1	...	0	...	1
14	326	287	321	1	...	2	...	1.5	...	1
16	331	309	322	2	...	6	...	4	...	1
2	323	300	317	...	1	...	5	...	3	1
18	349	329	323	5*	...	9	...	7	...	1
2	340	319	318	...	4	...	8	...	6	1
20	373	358	324	9	...	15	...	12	...	2
2	362	344	319	...	8	...	13	...	10.5	1
23	412	401	326	16	...	23	...	19.5	...	2
2	390	366	321	...	13	...	17	...	15	1
26	467	468	331	25*	...	34	...	29.5	...	3
2	421	404	325	...	18	...	23	...	20.5	2
30	...	...	360	...	...	...	...	...	...	8
2	...	...	355	...	...	...	...	...	...	7
49.02	...	...	...	...	...	...	...	...	...	...

\* Hole for the bolt was torn.

Taking into consideration the correction on account of the twist of the overlapping of the lap-joints in the space, the slip of the joint at the top edge is—

Load, Tons.	Slip in 0·002 Millimetre.	Load, Tons.	Slip in 0·002 Millimetre.
1 . . . . .	315-315=0	7 . . . . .	320-319=1
2 . . . . .	317-317=0	8 . . . . .	321-319=2
3 . . . . .	318-317=1	9 . . . . .	322-320=2
4 . . . . .	319-318=1	10 . . . . .	322-320=2
5 . . . . .	319-318=1	12 . . . . .	323-320=3
6 . . . . .	320-319=1	14 . . . . .	326-321=5

This table shows that the slip begins quite gradually, so that it cannot be ascertained exactly when it begins; therefore, it was not considered to have commenced till it had reached the amount of  $5 \times 0\cdot002 = 0\cdot01$  millimetre. For this reason the slip is not given in Table X. until the load has reached 14 tons.

Of these detailed tables only the average values of the elastic and permanent slip are entered in the tables for the groups of tests.



## VIII. TABLES OF RESULTS.

TABLE I.—*Series No. 1a. Single-riveted Lap-joint with three Nickel-Steel Rivets of 16 Millimetres Diameter, as in Fig. 16.*

Kind of nickel steel, A.

Uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 8 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 41,940 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 21,100 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 5700 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P : 3 \frac{d^2 \pi}{4}$
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		Kilogrammes.	
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
1	0	...	0	...	0	...	0	...	0	...	0	...	166	
2	0	...	0	...	0	...	0.5	...	0	...	0.1	...	332	
3	2	...	1	...	1	...	1.5	...	2	...	1.5	...	498	
4	3	...	2	...	2.5	...	2.5	...	3	...	2.6	...	664	
5	4.5	...	3	...	3.5	...	3.5	...	4	...	3.7	...	830	
6	5.5	2	4	2.5	4.5	1.5	5	2.5	5	2	4.8	2.1	996	
7	6.5	...	6	...	5.5	...	6	...	6	...	6.0	...	1162	
8	7.5	2	8	4	6.5	1.5	7	3	7	2	7.2	2.5	1328	
10	10	2.5	11	5	8	2.5	9.5	3.5	9.5	2	9.6	3.1	1660	
12	12.5	3.5	13	5	10	2.5	11.5	4	11	4	11.6	3.8	1992	
14	15	4	16	6	12.5	3.5	14	5	14	4.5	14.3	4.6	2324	
16	17.5	5	20	8	15	4	16	5.5	16	5.5	16.9	5.6	2656	
18	21	6.5	24	9	17.5	6	19	7	19	6.5	20.1	7.0	2980	
20	25	8	27	10	20.5	8	21.5	8.5	22.5	8.5	23.3	8.6	3320	
23	32	12	37	15	26	10	25.5	12	29.5	12.5	30.0	12.3	3820	
26	40	20	46	23	34	18	28	19	40	19.5	37.6	19.9	4320	

Breaking load in tons—Test No. (1) 43.200; (2) 38.000; (3) 43.780; (4) 43.660;

(5) 41.080; average, 41.940;  $P : 3 \frac{d^2 \pi}{4} = 6840$  kil. grammes.

Manner of breaking—Test No. (1) rivet-heads pulled through the plates; (2) rivet-holes sheared out; (3) and (4) rivet-heads pulled through the plates; (5) rivet-holes sheared out.



FIG. 15.—Series Ia1.

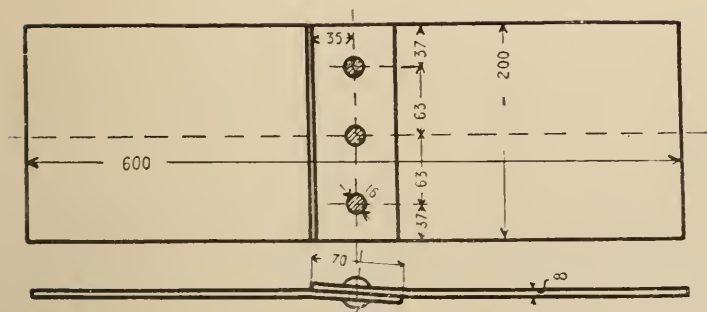


FIG. 16.



FIG. 17.—Series Ia5.

TABLE II.—*Series No. Ib. Single-riveted Lap-joint with three Nickel-Steel Rivets of 16 Millimetres Diameter, as in Fig. 16.*

Kind of nickel steel, C.

Uncaulked.

Riveting heat, light red.

Manner of riveting, hydraulic.

Maker of joint, F.

Thickness of plate, 8 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 27,530 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 21,100 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 5700 kilogrammes.

Slip in $\frac{1}{160}$ Millimetre.												$P:3\frac{d^2\pi}{4}$ Kilogrammes.	
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.		Permanent. Per Cent.
1	0	...	0	...	0	...	...	...	...	...	0	...	166
2	3	...	5	...	2	...	...	...	...	...	3.3	...	332
3	4.5	...	9	...	4.5	...	...	...	...	...	6.0	...	498
4	7	...	13	...	7	...	...	...	...	...	9.0	...	664
5	9	...	17.5	...	10.5	...	...	...	...	...	12.3	...	830
6	11.5	6	19	9.5	12	7	...	...	...	...	14.2	7.5	996
7	14	...	20.5	...	14.5	...	...	...	...	...	16.3	...	1162
8	15.5	8.5	22.5	11	16.5	8.5	...	...	...	...	18.2	9.3	1328
10	20	10.5	25.5	13	Mirror fell off.		...	...	...	...	22.7	11.3	1660
12	23.5	13	28.5	16.5	...	...	...	...	...	...	26.0	14.8	1992
14	27.5	16	31.5	17.5	...	...	...	...	...	...	29.5	16.8	2324
16	33	20.5	35	20	...	...	...	...	...	...	34.0	20.3	2656
18	37.5	24	38.5	22	...	...	...	...	...	...	38.0	23.0	2980
20	41.5	29.5	43	26	...	...	...	...	...	...	42.3	27.8	3320

Breaking load in tons—Test No. (1) 29.750 ; (2) 29.690 ; (3) 23.160 ; average, 27.530 ;  $P : 3 \frac{d^2 \pi}{4} = 4580$  kilogrammes.

Manner of breaking—Test No. (1) three rivet-heads broken off ; (2) two rivet-heads broken off ; (3) six rivet-heads broken off.

TABLE III.—*Series No. 1c. Single-riveted Lap-joint with three Nickel-Steel Rivets of 16 Millimetres Diameter, as in Fig. 16.*

Kind of nickel steel, D.

Uncaulked.

Riveting heat, light red.

Manner of riveting, pneumatic hammer.

Maker of joint, H.

Thickness of plate, 8 millimetres.

Average ultimate strength of the joint with nickel-steel rivets, 37,130 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 21,100 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 5700 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P : 3 \frac{d^2 \pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
1	0	...	0	...	0	...	...	...	...	...	0	...	166	
2	0	...	1	...	3	...	...	...	...	...	1.3	...	332	
3	0.5	...	2	...	4	...	...	...	...	...	2.2	...	498	
4	2	...	4	...	5.5	...	...	...	...	...	3.8	...	664	
5	3.5	...	6	...	6	...	...	...	...	...	5.2	...	830	
6	4.5	2.5	8.5	5	7.5	5	...	...	...	...	6.8	4.2	996	
7	6	...	10	...	9.5	...	...	...	...	...	8.5	...	1162	
8	7.5	3.5	11.5	5.5	10.5	6	...	...	...	...	9.8	5	1328	
10	9.5	4	16	7.5	14.5	7	...	...	...	...	13.3	6.2	1660	
12	12.5	5	18.5	8.5	17.5	9	...	...	...	...	16.2	7.5	1992	
14	15.5	6.5	22.5	11	21	11	...	...	...	...	19.7	9.5	2324	
16	18.5	7.5	26.5	13.5	25.5	13.5	...	...	...	...	23.5	11.5	2656	
18	23.5	10	33.5	17	31	17.5	...	...	...	...	29.3	14.8	2980	
20	28.5	14	41	24	38	24	...	...	...	...	35.8	20.7	3320	

Breaking load in tons—Test No. (1) 38.280; (2) 36.110; (3) 37.000; average, 37.130;  $P : 3 \frac{d^2 \pi}{4} = 6140$  kilogrammes.

Manner of breaking—Tests Nos. (1) (2) and (3) rivet-heads pulled through the plates.

TABLE IV.—*Series No. 1d. Single-riveted Lap-joint with three Nickel-Steel Rivets of 16 Millimetres Diameter, as in Fig. 16.*

Kind of nickel steel, A.

Uncaulked.

Riveting heat, light red.

Manner of riveting, by hand.

Maker of joint, G.

Thickness of plate, 8 millimetres.

Snap on head, 4.6 seconds, hammered by hand-hammer; 25.51 seconds by snap hammer.

Average ultimate strength of the joint with nickel-steel rivets, 44,260 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 21,100 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 5700 kilogrammes.

Slip in $\frac{1}{160}$ Millimetre.														$P:3\frac{d^2\pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
1	0	...	0	...	0	...	...	...	...	...	0	...	166	
2	0	...	0	...	0	...	...	...	...	...	0	...	332	
3	0.5	...	0.5	...	1	...	...	...	...	...	0.7	...	498	
4	1.5	...	2	...	1.5	...	...	...	...	...	1.7	...	664	
5	2.5	...	3	...	3	...	...	...	...	...	2.8	...	830	
6	4.5	3	4.5	2.5	4	1.5	...	...	...	...	4.3	2.3	996	
7	5.5	...	6	...	5.5	...	...	...	...	...	5.7	...	1162	
8	6.5	3	7.5	4	6.5	3	...	...	...	...	6.8	3.3	1328	
10	8.5	4	11	5.5	9.5	4	...	...	...	...	9.7	4.5	1660	
12	11	4.5	14	7.5	12.5	5.5	...	...	...	...	12.5	5.8	1992	
14	14	5.5	17	8.5	16	7	...	...	...	...	15.7	7.0	2324	
16	16.5	7	20.5	11.5	19.5	9	...	...	...	...	18.8	9.2	2656	
18	21	9	25	14	22.5	11.5	...	...	...	...	22.8	11.5	2980	
20	26	12	31	19	26	14.5	...	...	...	...	27.7	15.2	3320	

Breaking load in tons—Test No. (1) 43.450; (2) 44.410; (3) 44.930; average, 44.260;  $P : 3 \frac{d^2 \pi}{4} = 7330$  kilogrammes.

Manner of breaking—Test No. (1) plate tore between rivet-hole and edge of plate; (2) two rivets sheared; (3) two rivets sheared.

Fig. 18 shows the influence of the method of manufacture of the rivets on the slipping of uncaulked single lap-joints, with three nickel-steel rivets of 16 millimetres diameter. The electro-hydraulic riveting press (Series Ia) and hand-riveting (Series Id) give the best results, while the joints made by

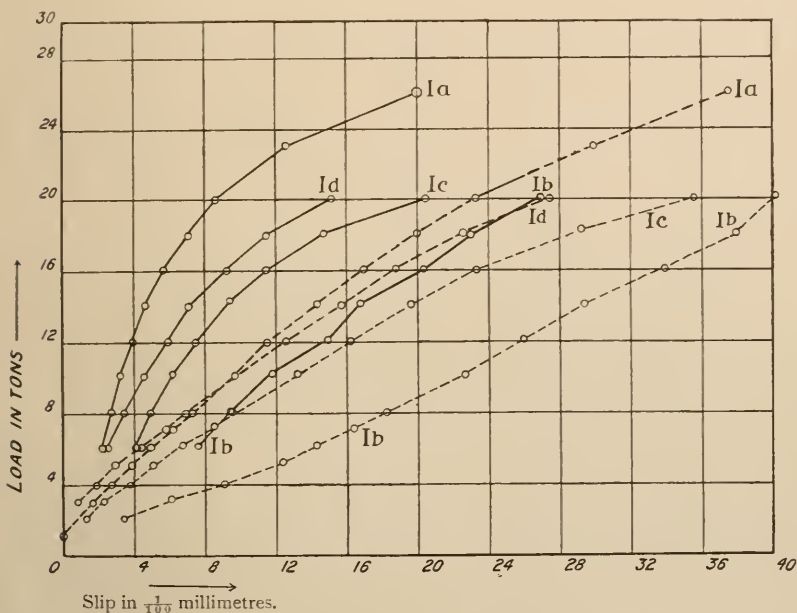


FIG. 18.—Influence of the Manner of Riveting. Single-riveted lap-joint with three nickel-steel rivets of 16 millimetres diameter. Ia, electro-hydraulic press. Ib, hydraulic press. Ic, pneumatic hammer. Id, by hand.

hydraulic and pneumatic presses showed a greater amount of slip.

It may be here pointed out that, strictly speaking, it is not allowable to draw any conclusions as to the relative value of the different kinds of riveting presses, pneumatic hammers or hand-riveting appliances from the diagrams, Figs. 18 to 32, which represent the slip of the plates on each other as a function of the load. As shown in nearly all the diagrams, the amount of slip is nearly the same for the joints made by all the different riveters, and the slight variations are



probably caused by different varieties of nickel steel being used in the various joints. Even if the same kind of nickel steel was used in each group of experiments, the difference of the surface of the plates coming from different workshops would have such an influence on the amount of slip, that no

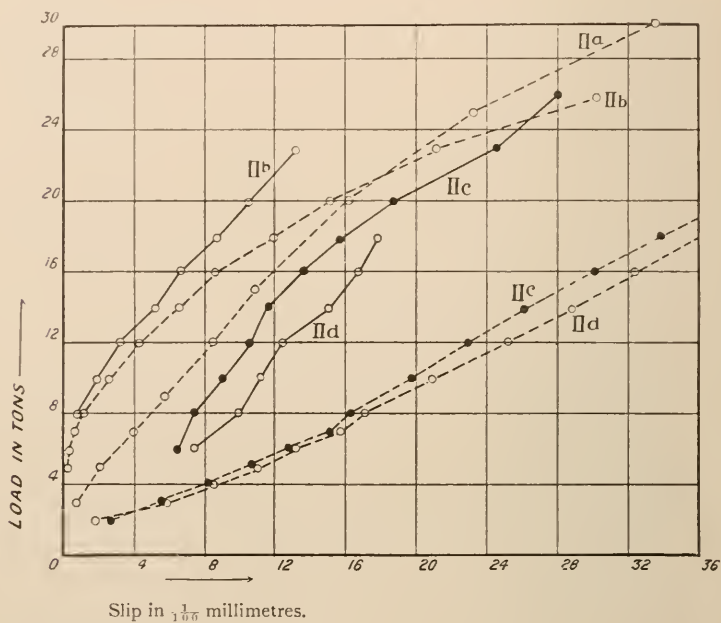


FIG. 19.—Influence of the Manner of Riveting. Single-riveted lap-joint with three nickel-steel rivets of 19 millimetres diameter (uncaulked). IIa, electro-hydraulic press. IIb, hydraulic press. IIc, pneumatic hammer. IIc, pneumatic hammer.

real comparison of the various methods of riveting could be obtained.

Fig. 19 shows the influence of the method of manufacture of the rivets on the slipping of unrimmed single-riveted lap-joints, with three nickel-steel rivets of 19 millimetres diameter. The electro-hydraulic (Series IIa) and hydraulic (Series IIb) presses gave the best results, while the joints made by pneumatic hammers showed a considerable slipping at a low load.

Fig. 20 shows the influence of the method of manufacture of the rivets on the slipping of caulked single-riveted lap-joints with three nickel-steel rivets of 19 millimetres diameter. The greatest amount of slip took place in joints riveted with pneumatic hammers (Series *Vc*), while the joints made by

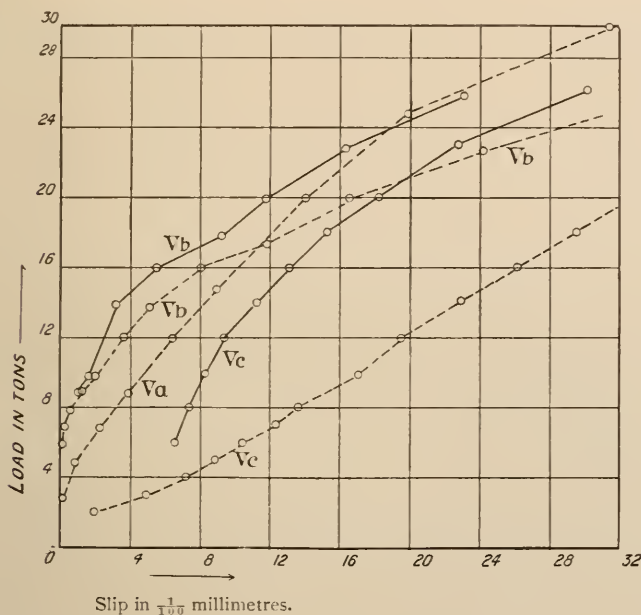


FIG. 20.—Influence of the Manner of Riveting. Single-riveted lap-joint with three nickel-steel rivets of 19 millimetres diameter (caulked). *Va*, electro-hydraulic press. *Vb*, hydraulic press. *Vc*, pneumatic hammer.

electro-hydraulic (Series *Va*) and hydraulic (Series *Vb*) presses showed better results.

Fig. 21 shows the result of caulking on single-riveted lap-joints with three nickel-steel rivets of 19 millimetres diameter. The joints in group II*a* were not caulked, those in group III had the rivet-heads caulked, those in group IV had the edges of the plate caulked, and in group V*a* both the rivet-heads and the edges of the plate were caulked. All the rivets were made with the electro-hydraulic press. At low

loads those joints show the least slip which had caulked rivet-heads and plate edges (Series  $Va$ ), or at least caulked rivet-heads.

Fig. 22 shows the influence of caulking on single-riveted lap-joints, with three nickel-steel rivets of 19 millimetres

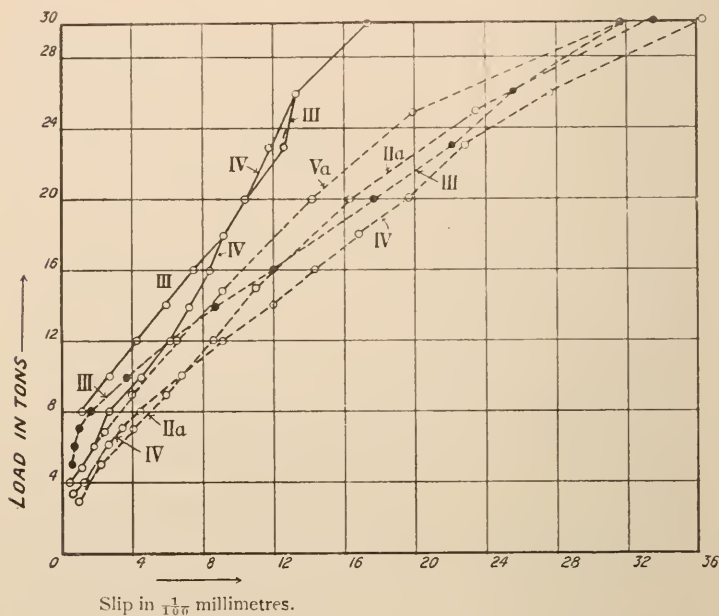


FIG. 21.—Influence of Caulking the Rivet-heads and Edge of Plate. Single-riveted lap-joint with three nickel-steel rivets of 19 millimetres diameter, made by electro-hydraulic press. IIa, uncaulked. III, rivet-heads caulked. IV, edge of plates caulked. Va, rivet-heads and edge of plate caulked.

diameter, that were made by hydraulic pressure. The joints in group IIb were not caulked, those in group Vb were. The caulking had a small favourable influence on the slip.

Fig. 23 shows in the same manner as Fig. 22 the influence of caulking on single-riveted lap-joints, with three nickel-steel rivets of 19 millimetres diameter, that were made with pneumatic hammers. The joints of group IIc were not caulked, those of group Vc were. A slight reduction in the slip can again be plainly noticed.

Fig. 24 shows the influence of artificially lengthening the rivet-shank by adding cover-pieces to a single-riveted lap-joint, with three nickel-steel rivets of 19 millimetres diameter, as in Fig. 23. The shanks are lengthened in this manner in group VI. and are left in their usual length in group II. The

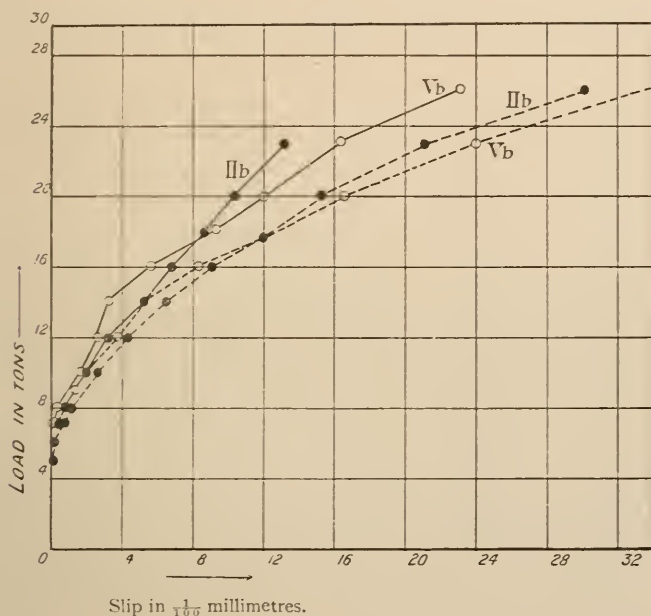


FIG. 22.—Influence of Caulking. Single-riveted lap-joint with three nickel-steel rivets of 19 millimetres diameter, made by hydraulic press. IIb, un-caulked. Vb, caulked.

joints with lengthened rivet-shank slipped decidedly more than the others.

Fig. 25 is a comparison of the slipping of joints riveted with nickel-steel rivets (Series IIa) and those riveted with wrought-iron rivets (Series VIIIa). Both groups were made in electro-hydraulic riveting presses. At small loads the slipping of the joints with nickel-steel rivets was greater than that of the joints with wrought-iron rivets. At 6.5 tons the slipping of both kinds of joints was the same. This load of 6.5

tons was smaller than the working-load of the joints riveted with wrought iron, for their ultimate strength is about 30 tons, and with a factor of safety of about 4 the joints may be loaded to 7 tons. At higher loads the slipping of the joints with nickel-steel rivets was decidedly less than that of the joints with wrought-iron rivets.

The curve of slip found by von Bach is likewise inserted in Fig. 25 for the sake of comparison. It may be here re-

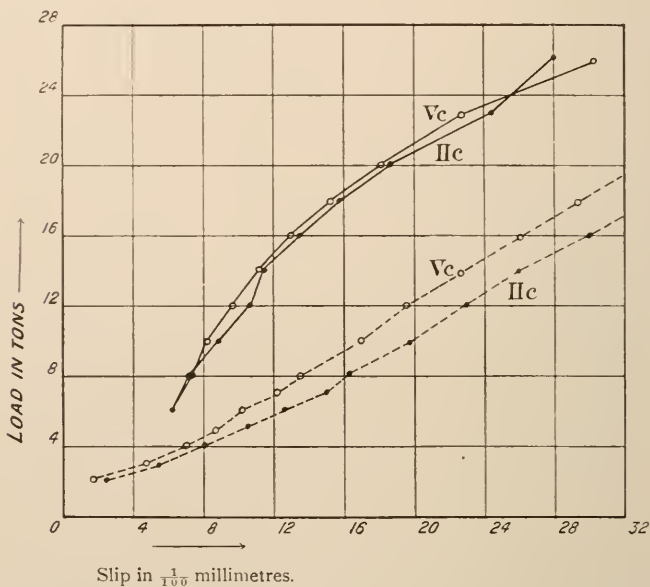


FIG. 23.—Influence of Caulking. Single-riveted lap-joint with three nickel-steel rivets of 19 millimetres diameter, made by pneumatic hammer. IIc, uncaulked. Vc, caulked.

marked that the wrought-iron joints in group VIIb. are designed according to von Bach's drawings. Von Bach's test showed the same amount of slip at a much higher load. Reference may be made to pp. 61–65 giving the summary of results for the probable reasons of this difference in the results obtained by von Bach and by the author.

Fig. 26 is like Fig. 25, a comparison of the slip of nickel-steel and wrought-iron single-riveted lap-joints with three

rivets of 19 millimetres diameter, which were made by hydraulic pressure. The curve of slip found by von Bach for joints with wrought-iron rivets is again inserted in the diagram. It will be seen that these joints made by hydraulic pressure have almost the same curve of slip as the joints tested by von Bach.

A comparison of the joints with wrought-iron rivets in Fig. 25 made by an electro-hydraulic press, and the joints with

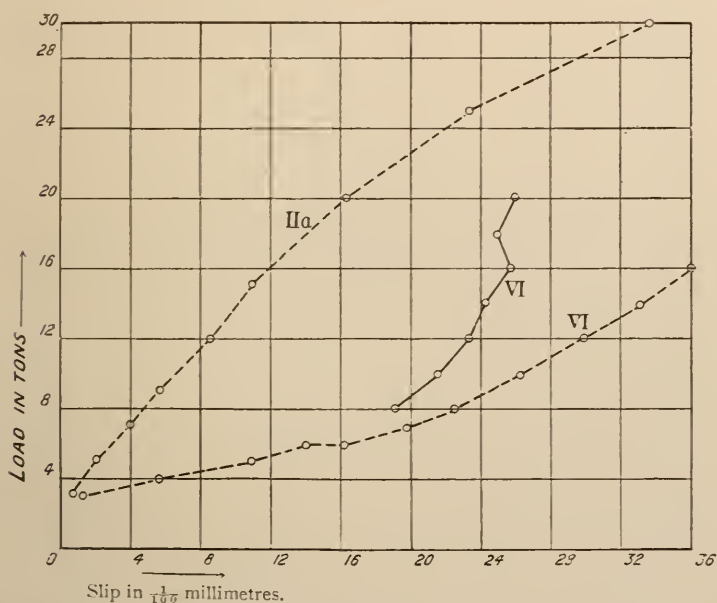


FIG. 24.—Influence of the Artificial Lengthening of the Rivet-shaft. Single-riveted lap-joint with three nickel-steel rivets of 19 millimetres diameter. IIa, rivet-shaft of normal length. VI, rivet-shaft lengthened.

wrought-iron rivets in Fig. 26 made by an hydraulic press, shows that the latter slipped much less than the former.

The slip of the wrought-iron and nickel-steel riveted joints in Fig. 26 is about the same at low loads, but, when highly loaded, the nickel-steel riveted joints slip decidedly the least.

Although the curve of slip of these wrought-iron riveted



joints made by hydraulic pressure is nearly coincident with the curve of slip found by von Bach, one important difference is that the slip begins much sooner in the author's tests. According to von Bach it did not begin in the joints under consideration until an average load of 9.7 tons had been

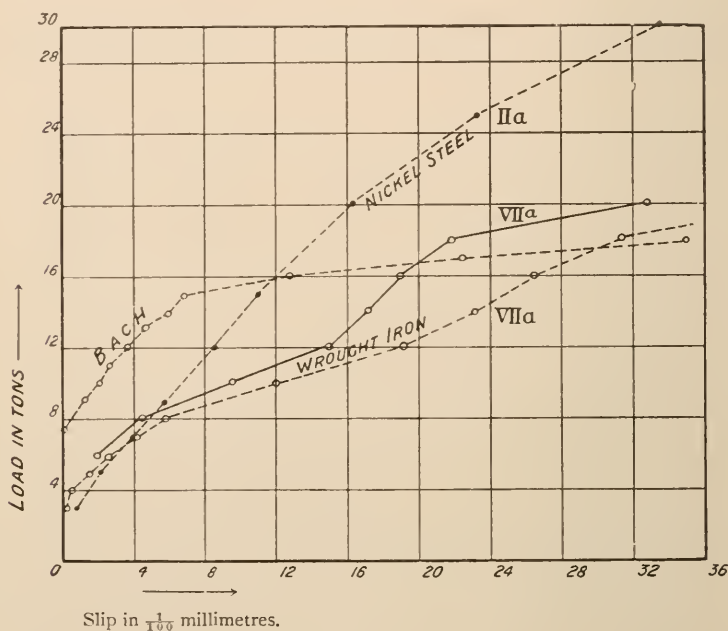


FIG. 25.—Comparison of Wrought-iron and Nickel-steel Rivets. Single-riveted lap-joint with three rivets of 19 millimetres diameter, made by electro-hydraulic press. IIa, nickel-steel rivets. VIIa, wrought-iron rivets.

reached, whereas of the eight wrought-iron riveted joints tested by the author only one did not start slipping until it was loaded to 10 tons, the remainder starting at much lower loads.

Fig. 27 shows the slipping of single-riveted lap-joints with three nickel-steel rivets of 25 millimetres diameter, made by various methods. Group VIIIa were made by electro-hydraulic presses, group VIIIb by hydraulic presses, and group VIIfc by pneumatic presses. Group VIIIa showed the least slip.

Fig. 28 is a comparison of the slip of single-riveted lap-joints with three nickel-steel rivets of various diameters. All the joints were made by electro-hydraulic presses. The slip of joints with thick rivets is only slightly less than that of joints with thin rivets, therefore joints with thick rivets are not so advantageous as those with thin ones. The relatively small resistance to slip of joints with thick rivets is pro-

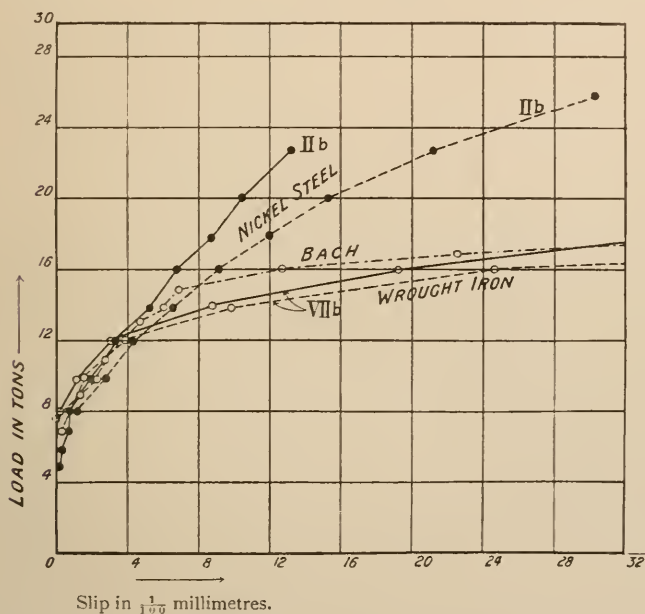


FIG. 26.—Comparison of Wrought-iron and Nickel-steel Rivets. Single-riveted lap-joint with three rivets of 19 millimetres diameter, made by hydraulic press. IIb, nickel-steel rivets. VIIb, wrought-iron rivets.

bably caused by the fact that thick rivets naturally are used with thick plates, which cannot be so firmly pressed together by the riveting-presses and rivets as thin ones, and therefore have not such a great resistance to slip.

Fig. 29 is, like Fig. 28, a comparison of the slip of single-riveted lap-joints with rivets of different diameters. The joints in this diagram were hydraulically riveted. In this case, at equal loads the joints with rivets having a diameter

of 19 millimetres slipped much less than those with rivets of 16 millimetres or 25 millimetres diameter.

Fig. 30 shows the curve of slip of a double-riveted lap-joint with five rivets of 19 millimetres diameter which were made by hydraulic pressure.

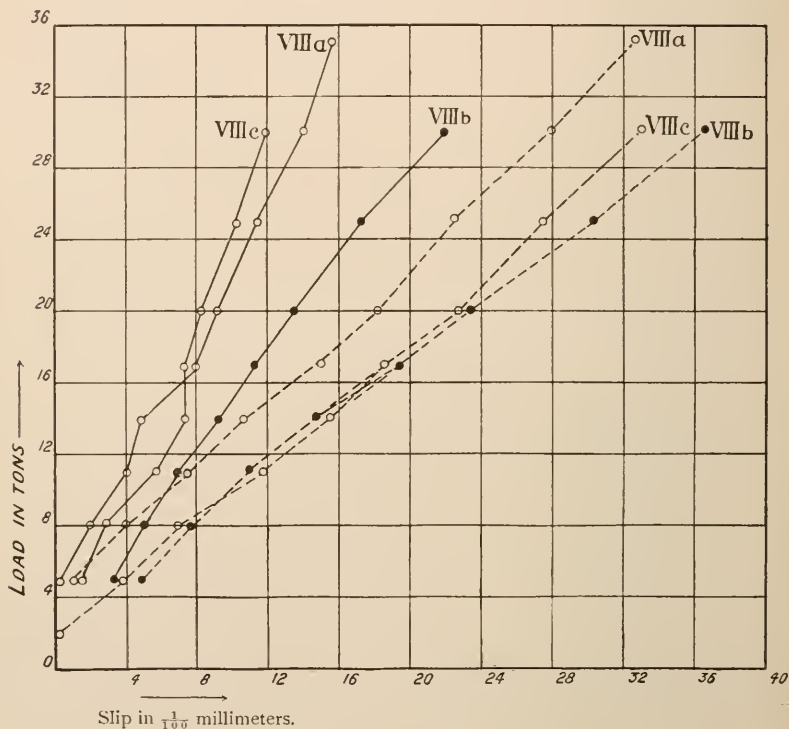


FIG. 27.—Influence of the Manner of Riveting. Single-riveted lap-joint with three nickel-steel rivets of 25 millimetres diameter. VIIIa, electro-hydraulic press. VIIIb, hydraulic press. VIIIc, pneumatic press.

Fig. 31 shows the slip of single-riveted butt-joints with four nickel-steel rivets made by different methods (hydraulic pressure, pneumatic hammers, and by hand). The different groups do not show much difference in the amount of slip. The ultimate strength of the joints is about 40 tons. The single-riveted lap-joints, with three rivets of 16 millimetres

diameter, shown in Fig. 18, have about the same ultimate strength of 40 tons. A comparison of Fig. 18 with Fig. 31 shows that the curve of slip lies lower in Fig. 31 than in Fig. 18—that is to say, at equal loads the slip of butt-joints is greater than that of lap-joints. This has the following result, as already determined by von Bach, that in riveted

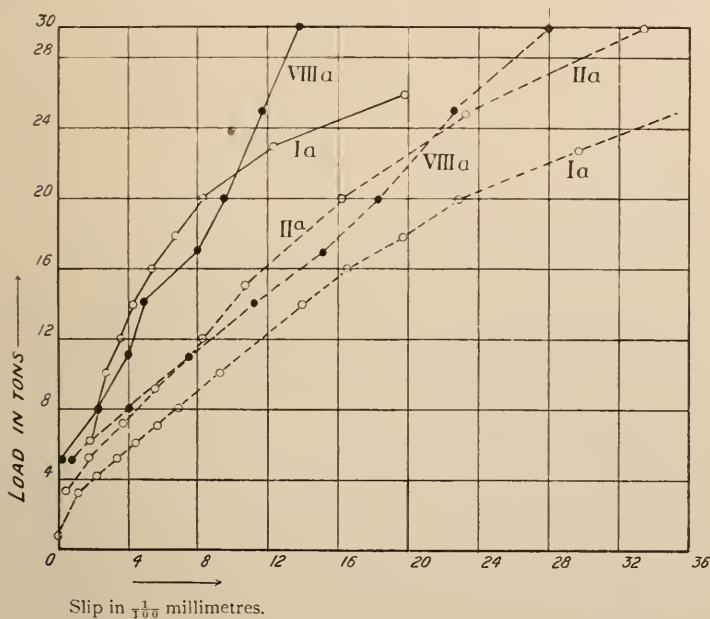


FIG. 28.—Comparison of Rivets with Different Diameter of Shaft. Single-riveted lap-joint with three nickel-steel rivets, made by electro-hydraulic press. Ia, diameter of rivet, 16 millimetres. IIa, diameter of rivet, 19 millimetres. VIIa, diameter of rivet, 25 millimetres.

joints with the same ultimate strength the amount of slip of butt-joints is greater than that of lap-joints.

Fig. 32 shows the slip of single-riveted butt-joints with four nickel-steel rivets which were made either by hydraulic pressure or with pneumatic hammers. The former slipped less than the latter. The ultimate strength of these joints was about 60 tons. The single-riveted lap-joints in Fig. 19, with three nickel-steel rivets of 19 millimetres diameter, have

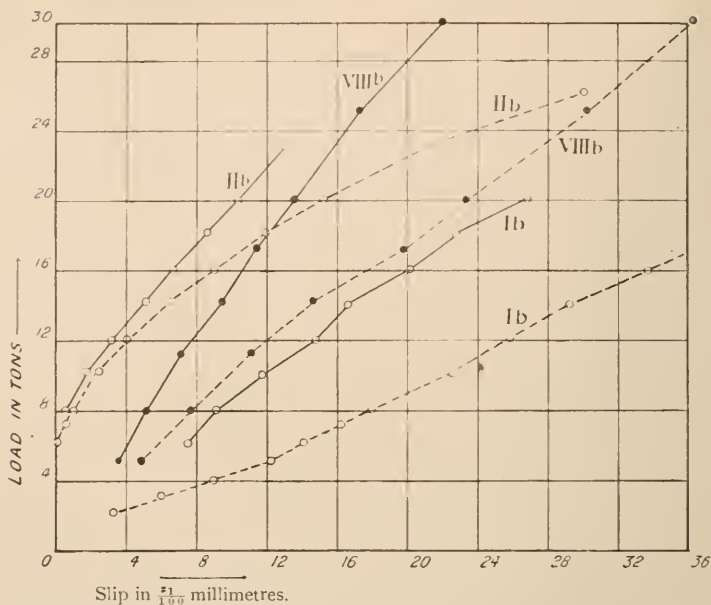


FIG. 29.—Comparison of Rivets with Different Diameter of Shaft. Single-riveted lap-joint with three nickel-steel rivets, made by hydraulic press. Ib, diameter of rivet, 16 millimetres. IIb, diameter of rivet, 19 millimetres. VIIIb, diameter of rivet, 25 millimetres.

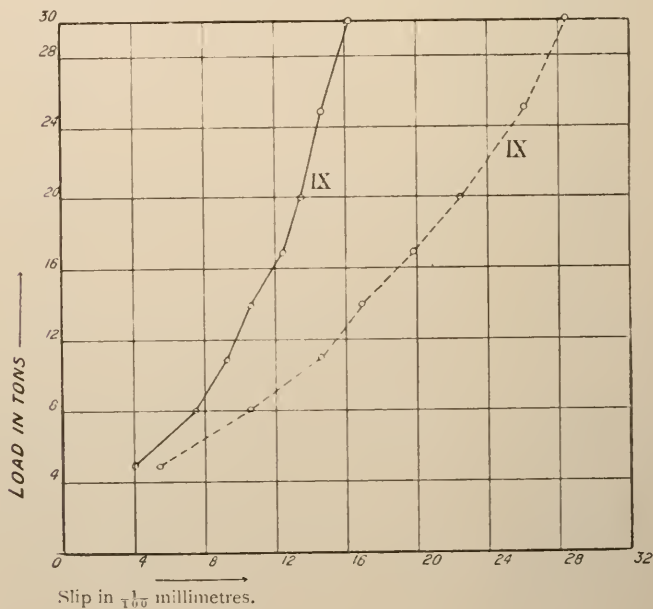


FIG. 30.—Double-riveted Lap-joint with Five Rivets of 19 Millimetres Diameter, made by Electro-hydraulic Press.

about the same ultimate strength. A comparison of Fig. 32 with Fig. 19 shows, as has already been pointed out in con-

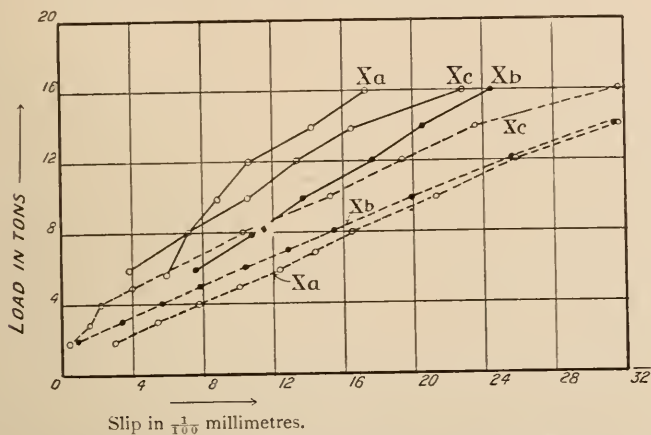


FIG. 31.—Influence of the Manner of Riveting. Single-riveted butt-joint with four nickel-steel rivets of 16 millimetres diameter. Xa, hydraulic. Xb, pneumatic hammer. Xc, by hand.

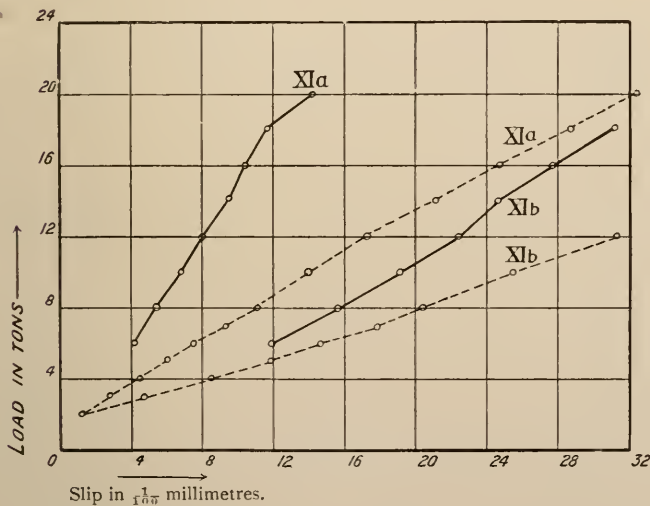


FIG. 32.—Influence of the Manner of Riveting. Single-riveted butt-joint with four nickel-steel rivets of 19 millimetres diameter. XIa, hydraulic. XIb, pneumatic hammer.

nection with Fig. 31, that the ultimate strength being the same, butt-joints slip more than lap-joints.



TABLE V.—*Series No. IIa. Single-riveted Lap-joint, with three Nickel-Steel Rivets of 19 Millimetres Diameter, as in Fig. 33.*

Kind of nickel steel, B.

Uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 53,830 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,200 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9700 kilogrammes.

Load, P Tons.	Slip in $\frac{1}{100}$ Millimetre.												$P : 3 \frac{d^2 \pi}{4}$  Kilogrammes.
	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
3	0	...	0	...	1	...	1	...	1.5	...	0.7	...	354
5	0	...	1.5	...	3	...	3	...	4	...	2	...	590
7	0	...	3	...	5	...	5	...	6.5	...	3.9	...	826
9	2	...	5	...	7	...	6.5	...	8	...	5.7	...	1062
12	5	...	7.5	...	10	...	9	...	11	...	8.5	...	1416
15	7	...	10	...	13	...	11	...	13.5	...	10.9	...	1770
20	12	...	15	...	18	...	17	...	19.5	...	16.3	...	2360
25	19	...	22	...	26	...	23	...	27	...	23.4	...	2950
30	29.5	...	33	...	35	...	35	...	36	...	33.7	...	3540

Breaking load in tons—Test No. (1) 54.500; (2) 55.450; (3) 50.720; (4)

52.000; (5) 56.460; average, 53.830;  $P : 3 \frac{d^2 \pi}{4} = 6320$  kilogrammes.

Manner of breaking—Tests Nos. 1-5, plate broke through the rivet-holes.

TABLE VI.—*Series No. IIb. Single-riveted Lap-joint, with three Nickel-Steel Rivets of 19 Millimetres Diameter, as in Fig. 33.*

Kind of nickel steel, A.

Uncaulked.

Riveting heat, light red.

Manner of riveting, hydraulic.

Maker of joint, F.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 52,570 kilograms.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,200 kilograms.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9700 kilograms.

Slip in $\frac{1}{100}$ Millimetre.													$P : 3 \frac{d^2 \pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
1	0	...	0	...	0	...	...	...	...	...	0	...	118
2	0	0	0	0	0	0	...	...	...	...	0	0	236
3	0	...	0	...	0	...	...	...	...	...	0	...	354
4	0	0	0	0	0	0	...	...	...	...	0	0	472
5	0	...	0	...	0.5	...	...	...	...	...	0.2	0	590
6	0	0	0	0	1	0	...	...	...	...	0.3	0	708
7	0	...	0	...	2	...	...	...	...	...	0.7	...	826
8	0.5	0	0	0	2.5	2	...	...	...	...	1	0.7	944
10	2.5	1.5	0	0	5	4	...	...	...	...	2.5	1.8	1180
12	5	4	0.5	0	7	5.5	...	...	...	...	4.2	3.2	1416
14	7.5	6.5	1.5	1.5	10.5	7.5	...	...	...	...	6.5	5.2	1652
16	10.5	8	3.5	3.5	13	8.5	...	...	...	...	9	6.7	1888
18	13	9.5	7	7	16	9.5	...	...	...	...	12	8.7	2120
20	16	11	11	9.5	19	11	...	...	...	...	15.3	10.5	2360
23	21	12.5	17.5	14	25	13	...	...	...	...	21.2	13.2	2720
26	30	17.5	25	...	36	23	...	...	...	...	30.3	...	3070

Breaking load in tons—Test No. (1) 52.970; (2) 52.940; (3) 51.800; average, 52.570;  $P : 3 \frac{d^2 \pi}{4} = 6200$  kilograms.

Manner of breaking—Tests Nos. 1-3, hole for the bolt torn.

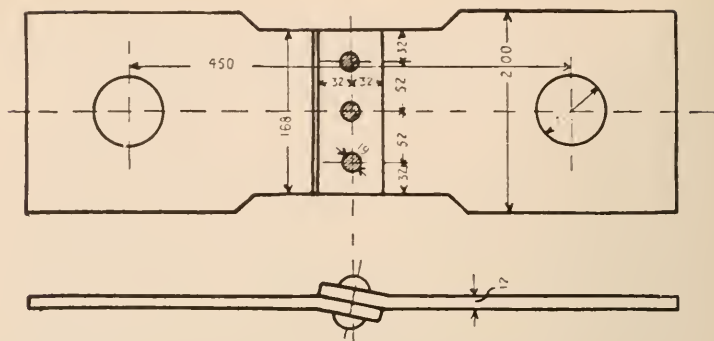


FIG. 33.



FIG. 34.—IIa3.

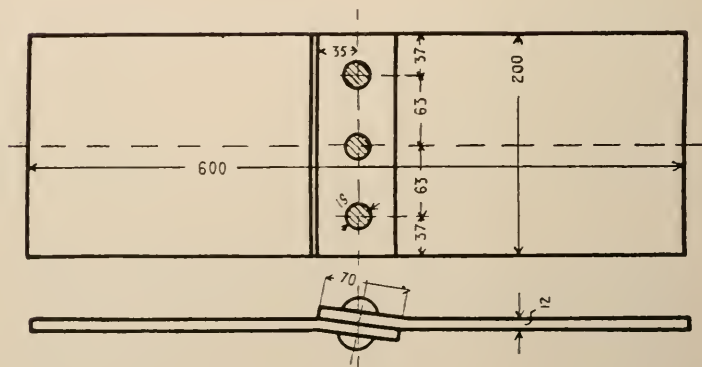


FIG. 35.

TABLE VII.—*Series No. IIc. Single-riveted Lap-joint, with three Nickel-Steel Rivets of 19 Millimetres Diameter, as in Fig. 35.*

Kind of nickel steel, D.\*

Uncaulked.

Riveting heat, cherry-red.

Manner of riveting, pneumatic.

Maker of joint, H.

Thickness of plate, 12 millimetres.

Average ultimate strength of the joint with nickel-steel rivets, 48,650 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,200 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9700 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.															P: $3\frac{d^2\pi}{4}$ Kilogrammes
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.				
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.			
1	0	...	0	...	0	...	...	...	...	...	0	...	118		
2	2	...	1.5	...	4	...	...	...	...	...	2.5	...	236		
3	3	...	5	...	8.5	...	...	...	...	...	5.5	...	354		
4	5	...	7.5	...	12	...	...	...	...	...	8.2	...	472		
5	7	...	10.5	...	14.5	...	...	...	...	...	10.7	...	590		
6	8	4.5	13.5	6.5	16.5	8	...	...	...	...	12.7	6.3	708		
7	9.5	...	17	...	19	...	...	...	...	...	15.2	...	826		
8	10.5	5	18	7.5	20.5	9	...	...	...	...	16.3	7.2	944		
10	13	6	22.5	10	23.5	10.5	...	...	...	...	19.7	8.8	1180		
12	16.5	8	26.5	12	26	11.5	...	...	...	...	23.0	10.5	1416		
14	19	8	30	13.5	29	13	...	...	...	...	26.0	11.5	1652		
16	22.5	9	35	16	32.5	15.5	...	...	...	...	30.0	13.5	1888		
18	25.5	11	39.5	19	36.5	17	...	...	...	...	33.8	15.7	2120		
20	30.5	13.5	44	22	40	20.5	...	...	...	...	38.2	18.7	2360		
23	36.5	19	53.5	28.5	48	26	...	...	...	...	46.0	24.5	2720		
26	46	23	...	...	55	33	...	...	...	...	50.5	28.0	3070		

Breaking load in tons—Test No. (1) 45.000; (2) 52.310; (3) 28.000; average, 48.650;  $P: 3\frac{d^2\pi}{4} = 5730$  kilogrammes.

Manner of breaking—Tests Nos. 1-3, two rivet-heads broken off.

\* Test No. 3. Kind of nickel steel, C. Result of Test No. 3 not used for the average.

TABLE VIII.—*Series No. III. Single-riveted Lap-joint, with three Nickel-Steel Rivets of 19 Millimetres Diameter, as in Fig. 35.*

Kind of nickel steel, D.

Uncaulked.

Riveting heat, light red.

Manner of riveting, pneumatic.

Maker of joint, H.

Thickness of plate, 12 millimetres.

Average ultimate strength of the joint with nickel-steel rivets, 55,540 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,200 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9700 kilogrammes.

Load, P Tons.	Slip in $\frac{1}{100}$ Millimetre.												$P: 3\frac{d^2\pi}{4}$  Kilogrammes.
	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Perm. nent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
1	0	...	0	...	0	...	...	...	...	...	0	...	118
2	2	...	1.5	...	2	...	...	...	...	...	1.8	...	236
3	6	...	4.5	...	6.5	...	...	...	...	...	5.7	...	354
4	9	...	6.5	...	9.5	...	...	...	...	...	8.3	...	472
5	12.5	...	8	...	12	...	...	...	...	...	10.8	...	590
6	15	8	10	6	14	7.5	...	...	...	...	13.0	7.3	708
7	18	...	12	...	16.5	...	...	...	...	...	15.5	...	826
8	19.5	13.5	13.5	7	17.5	9	...	...	...	...	16.8	9.8	944
10	23.5	13.5	16.5	9	22	10.5	...	...	...	...	20.7	11.0	1180
12	29	13.5	19.5	11	26.5	12.5	...	...	...	...	25.0	12.3	1416
14	31	18	23	12.5	32	14.5	...	...	...	...	28.7	15.0	1652
16	35.5	18	26	15	35	17	...	...	...	...	32.2	16.7	1888
18	39.5	18.5	30	15.5	39.5	19	...	...	...	...	36.3	17.7	2110
20	49.5	26	...	...	45	23	...	...	...	...	47.3	24.5	2360
23	52	28	...	...	51.5	28	...	...	...	...	51.8	28.0	2720
26	59.5	35	...	...	...	...	...	...	...	...	59.5	35.0	3070

Breaking load in tons—Test No. (1) 53.310; (2) 53.120; (3) 60.200; average, 55.540;  $P: 3\frac{d^2\pi}{4} = 6570$  kilogrammes.

Manner of breaking—Tests Nos. 1-3, one rivet-hole sheared out.

TABLE IX.—*Series No. III. Single-riveted Lap-joint with three Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 35.*

Kind of nickel steel, A.

Heads caulked, plates uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 64,250 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,700 kilogrammes.

Result of Test No. 2 not used for the average.

Slip in $\frac{1}{100}$ Millimetre.														P: $3 \frac{d^2 \pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.		
1	0	...	0	...	0	...	0	...	0	...	0	...	118	
2	0	...	2	...	0	...	0	...	0	...	0	...	236	
3	0	...	3	...	0	...	0	...	0	...	0	...	354	
4	0	0	4.5	3	0.5	0	0	0	0.5	0	0.3	0	472	
5	0	...	6.5	...	1	...	0	...	0.5	...	0.4	...	590	
6	0	0	7.5	3.5	1	0	0	0	1	0	0.5	0	708	
7	0.5	...	8.5	...	1	...	0	...	1.5	...	0.8	...	826	
8	1	0.5	9.5	4.5	2.5	2	0.5	0	2.5	1.5	1.6	1	944	
10	3	2	12	4.5	5.5	4.5	1.5	1	4	2.5	3.5	2.5	1180	
12	5	3.5	14	5.5	10	6.5	4	2.5	6	4	6.3	4.1	1416	
14	7.5	5.5	16	6	12	7	6.5	5	8	5.5	8.5	5.8	1652	
16	11	7	18	6.5	15	8.5	10	7	11.5	7	11.9	7.4	1888	
18	12.5	8.5	20	7	18	9	13	9	14.5	9.5	14.5	9.0	2120	
20	15	9	21.5	8	20.5	10.6	16	10.5	19	12	17.6	10.4	2360	
23	19	10	26	10	24.5	11.5	20	12	24.5	15.5	22.0	12.3	2720	
26	22.5	12.5	30.5	12.5	28	12.5	24.5	14	28	14.5	25.7	13.4	3070	
30	28.5	15.5	37	...	34	15.5	31.5	17	33.5	21.5	31.8	17.4	3540	

Breaking load in tons—Test No. (1) 66.800; (2) 62.200; (3) 66.360; (4) 62.280;

(5) 63.620; average, 64.250;  $P: 3 \frac{d^2 \pi}{4} = 7550$  kilogrammes.

Manner of breaking—Test No. (1) plate broke through the rivet-holes between rivet-hole and edge of plate; (2) plate broke through the rivet-holes; (3) rivet-heads pulled through the plates; (4) plate broke through the rivet-holes; (5) plate broke through the rivet-holes.



TABLE X.—*Series No. IV. Single-riveted Lap-joint with three Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 35.*

Kind of nickel steel, A.

Plates caulked, heads uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 58,710 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,700 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 11,000 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P:3 \frac{d^2\pi}{4}$  Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
1	0	...	0	...	0	...	0	...	0	...	0	...	118	
2	0	0	0	0	0	0	0	0	0	0	0	0	236	
3	0	...	0	...	0.5	...	0.5	...	1	0	0.4	...	354	
4	0	0	0.5	0	1.5	0	1.5	0	1.5	1.5	1.0	0.3	472	
5	0	...	1	...	2	...	3	...	3	...	1.8	...	590	
6	0	0	2	0	3	2.5	4	3	3.5	2.5	2.5	1.6	708	
7	0	...	3	...	4.5	...	4.5	...	4.5	...	3.3	...	826	
8	0.5	0	4.5	3.5	5.5	4	6	4	5	4	4.3	3.1	944	
10	2	1	7.5	6.5	8	4.5	9	5.5	7	4	6.7	4.3	1180	
12	4.5	4	10.5	7.5	10	6	11	7	9	6	9	6.1	1416	
14	8	6	13	8	12.5	7	14	7.5	11.5	7	11.8	7.1	1652	
16	10.5	8	16	9	15	8	16	8	13.5	8.5	14.2	8.3	1888	
18	13	9	19	9.5	17	8.5	18.5	9	16.5	9.5	16.8	9.1	2120	
20	16	10.5	21.5	10.5	19.5	9.5	21.5	9.5	20.5	11.5	19.8	10.3	2360	
23	20	11	24	11.5	24	10.5	26	11	20	14	22.8	11.6	2720	
26	25	12.5	29.5	13	29.5	12.5	30.5	13	24	15	27.7	13.2	3070	
30	33	16.5	36.5	16	40	18.5	41	18	31	17	36.3	17.2	3540	

Breaking load in tons—Test No. (1) 57.950; (2) 58.560; (3) 57.960; (4) 59.080;

(5) 60.020; average, 58.710;  $P : 3 \frac{d^2 \pi}{4} = 6900$  kilogrammes.

Manner of breaking—Tests Nos. 1-5 plate broke through the rivet-holes.



FIG. 36.—Series II12.



FIG. 37.—Series Va.

TABLE XI.—*Series No. Va. Single-riveted Lap-joint with three Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 33.*

Kind of nickel steel, B.

Caulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic

Maker of joint, E.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 54,640 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,200 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 14,000 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.													$P: 3 \frac{d^2 \pi}{4}$  Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
3	0	...	0	...	0	...	0	...	1	...	0·2	...	354
5	1	...	0·5	...	0·5	...	0·5	...	2	...	0·9	...	590
7	2	...	2	...	2	...	1·5	...	4	...	2·3	...	826
9	4	...	3·5	...	3·5	...	3·5	...	5·5	...	4·0	...	1062
12	6	...	6·5	...	6·5	...	5·5	...	8	...	6·5	...	1416
15	8	...	9	...	9	...	8	...	11	...	9	...	1770
20	15	...	14	...	14·5	...	12	...	16	...	14·3	...	2360
25	19·5	...	20	...	20	...	18	...	23	...	20·1	...	2950
30	30	...	33	...	30·5	...	28	...	37	...	31·7	...	3540

Breaking load in tons—Test No. (1) 57·880; (2) 55·140; (3) 55·250; (4) 53·400;

(5) 51·520; average, 54·640;  $P: 3\frac{d^2\pi}{4} = 6410$  kilogrammes.

Manner of breaking—Tests Nos. 1 to 5 plate broke through the rivet-holes.

TABLE XII.—*Series No. Vb. Single-riveted Lap-joint with three Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 33.*

Kind of nickel steel, A.

Caulked.

Riveting heat, light red.

Manner of riveting, hydraulic.

Maker of joint, F.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 51,807 kilograms.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,200 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 14,000 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P : 3 \frac{d^2 \pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
1	0	...	0	...	0	...	...	...	...	...	0	...	118	
2	0	0	0	0	0	0	...	...	...	...	0	0	236	
3	0	...	0	...	0	...	...	...	...	...	0	...	354	
4	0	0	0	0	0	0	...	...	...	...	0	0	472	
5	0	...	0	...	0	...	...	...	...	...	0	...	590	
6	0	0	0	0	0.5	0	...	...	...	...	0.2	0	708	
7	0	...	0	...	1	...	...	...	...	...	0.3	...	826	
8	0	0	0	0	2	1.5	...	...	...	...	0.6	0.5	944	
9	0	...	0	...	4	...	...	...	...	...	1.3	...	1060	
10	0.5	0	0	0	5.5	5.5	...	...	...	...	2.0	1.8	1180	
12	1.5	1	0.5	0	9.5	7	...	...	...	...	3.8	2.7	1416	
14	2.5	1.5	1.5	0	12	8.5	...	...	...	...	5.3	3.3	1652	
16	5.5	4.5	4	3	15.5	11	...	...	...	...	8.3	5.7	1888	
18	10	8.5	7	6	20	13.5	...	...	...	...	12.3	9.3	2120	
20	14	11	12	10.5	24	14.5	...	...	...	...	16.7	12.0	2360	
23	21.5	14	19.5	15	32	20.5	...	...	...	...	24.3	16.5	2720	
26	32	21	29.5	20.5	43	28.5	...	...	...	...	34.8	23.3	3070	

Breaking load in tons—Test No. (1) 53.900; (2) 49.020; (3) 52.500; average, 51.807;  $P : 3 \frac{d^2 \pi}{4} = 6100$  kilogrammes.

Manner of breaking—Test No. (1) plate broke through the rivet-holes; (2) and (3) hole for the bolt torn.

TABLE XIII.—*Series No. Vc. Single-riveted Lap-joint with three Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 35.*

Kind of nickel steel, D.

Caulked.

Riveting heat, light red.

Manner of riveting, pneumatic hammer.

Maker of joint, H.

Thickness of plate, 12 millimetres.

Average ultimate strength of the joint with nickel-steel rivets, 47,940 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,200 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 14,000 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P:3\frac{d^2\pi}{4}$  Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
1	0	...	0	...	0	...	...	...	...	...	0	...	118	
2	1.5	...	2.5	...	1.5	...	...	...	...	...	1.8	...	236	
3	4	...	5.5	...	5	...	...	...	...	...	4.8	...	354	
4	6	...	8	...	7	...	...	...	...	...	7.0	...	472	
5	7.5	...	10	...	9	...	...	...	...	...	8.8	...	590	
6	8.5	6	12	8	10.5	5	...	...	...	...	10.3	6.3	708	
7	11	...	14	...	11.5	...	...	...	...	...	12.2	...	826	
8	12	7	15	9	13.5	6	...	...	...	...	13.5	7.3	944	
10	15.5	8.5	19.5	10	16	6.5	...	...	...	...	17.0	8.3	1180	
12	18	9	22	12	18.5	7	...	...	...	...	19.5	9.3	1416	
14	22	11.5	25	13.5	21.5	8.5	...	...	...	...	22.8	11.2	1652	
16	25	13	29	15	24.5	11	...	...	...	...	26.2	13.0	1888	
18	28.5	15	32.5	15.5	27.5	15.5	...	...	...	...	29.5	15.3	2120	
20	33	18.5	36.5	19	30.5	17	...	...	...	...	33.3	18.2	2360	
23	40.5	23	43.5	24	37.5	21.5	...	...	...	...	40.5	22.8	2720	
26	50.5	31	52.5	31.5	47	28.5	...	...	...	...	50.0	30.3	3070	

Breaking load in tons—Test No. (1) 50.230; (2) 47.600; (3) 46.000; average, 47.940;  $P:3\frac{d^2\pi}{4}=5630$  kilogrammes.

Manner of breaking—Test No. (1) head of one rivet off; (2) heads of two rivets off; (3) head of one rivet off.

TABLE XIV.—*Series No. VI. Single-riveted Lap-joint with three Nickel-steel Rivets of 19 Millimetres Diameter and Covers, as in Fig. 38.*

Kind of nickel steel, D.

Uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 58,570 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 29,000 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 12,900 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P : 3 \frac{d^2\pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent, Per Cent.	Elastic. Per Cent.	Permanent, Per Cent.	Elastic. Per Cent.	Permanent, Per Cent.	Elastic. Per Cent.	Permanent, Per Cent.	Elastic. Per Cent.	Permanent, Per Cent.	Elastic. Per Cent.	Permanent, Per Cent.	Permanent, Per Cent.	
2	0	...	0	...	0	...	0	...	0	...	0	...	236	
3	1	...	3.5	...	0	...	1	...	1	...	1.3	...	354	
4	3	...	9.5	...	2	...	6	...	7.5	...	5.6	...	472	
5	8	...	15.5	...	5.5	...	11	...	15	...	11	...	590	
6	15	13	19.5	17.5	11	8	15	13	20.5	19	16.2	14.1	708	
7	20.5	...	22.5	...	14	...	17.5	...	25	...	19.9	...	826	
8	25.5	22.5	24.5	20	16.5	14	20	16.5	27	23.5	22.7	19.3	944	
10	31	27	27.5	21.5	21	17.5	22.5	17.5	30.5	24.5	26.5	21.6	1180	
12	35.5	30.5	31	22.5	24.5	18.5	25.5	19.5	34.5	26	30.2	23.4	1416	
14	40.5	32	33	22.5	27.5	20.5	28.5	19.5	37.5	27.5	33.4	24.4	1652	
16	43.5	34.5	35.5	23.5	30	21.5	31.5	21	40.5	29	36.2	25.9	1888	
18	...	...	39	25.5	32.5	22	35	23	43	30	37.4	25.1	2120	
20	...	...	41.5	25.5	37.5	24	41.5	25	46	30	41.6	26.1	2360	

Breaking load in tons—Test No. (1) 58.320; (2) 59.480; (3) 59.090; (4) 58.700;

(5) 57.260; average, 58.570;  $P : 3 \frac{d^2\pi}{4} = 6880$  kilogrammes.Manner of breaking—Test No. (1) three rivets sheared; (2) two rivets sheared;  
(3) two rivets sheared; (4) three rivets sheared; (5) two rivets sheared.



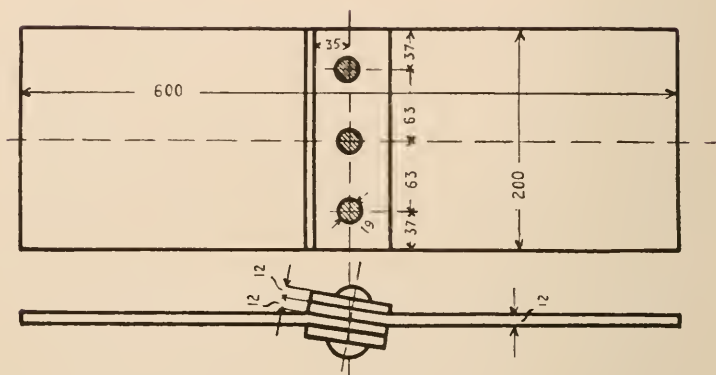


FIG. 38.

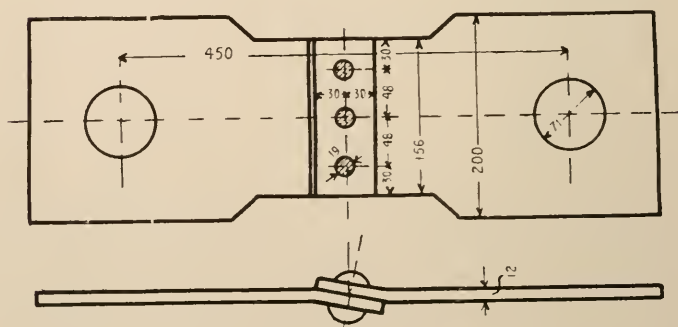


FIG. 39.

TABLE XV.—*Series No. VIIa. Single-riveted Lap-joint with three Wrought-iron Rivets of 19 Millimetres Diameter, as in Fig 39.*

Wrought-iron rivets.

Uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with wrought-iron rivets, 32,740 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9700 kilogrammes.

Slip in $\frac{1}{160}$ Millimetre.														P: $3\frac{d^2\pi}{4}$
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		Kilogrammes.	
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
1	0	...	0	...	0	...	0	...	0	...	0	...	118	
2	0	...	0	...	0	...	0	...	0	...	0	...	236	
3	0	...	0	...	0.5	...	0	...	0	...	0.1	...	354	
4	0	...	0	...	1	...	0.5	...	0	...	0.3	...	472	
5	0.5	...	2	...	2.5	...	2	...	0	...	1.4	...	590	
6	1.5	1	3	2	3.5	3.5	3	2.5	1	0	2.4	1.8	708	
7	2.5	...	4	...	6	...	5	...	2.5	...	4	...	826	
8	4	3	5.5	4.5	8	6.5	7	5	4	3	5.7	4.4	944	
10	8.5	7	12	9.5	17	13	15	11.5	7.5	6.5	12	9.5	1180	
12	18	14.5	19	14	25	19	19.5	14	14.5	13	19.2	14.9	1416	
14	21.5	16.5	23	17	28	20	22.5	15.5	21	17	23.2	17.2	1652	
16	25	18	26	19	31.5	21.5	26	17.5	24.5	19	26.6	19	1888	
18	30.5	21	30	20	37.5	25.5	...	...	28	21	31.5	21.9	2120	
20	46	33	40	28	59.5	44.5	...	...	36	26	45.4	32.9	2360	

Breaking load in tons—Test No. (1) 30.800; (2) 35.000; (3) 29.300; (4) 35.760;

(5) 32.840; average, 32.740;  $P: 3\frac{d^2\pi}{4} = 3840$  kilogrammes.

Manner of breaking—Test No. (1) hole for the bolt torn; (2) three rivets sheared; (3) hole for the bolt torn; (4) two rivets sheared; (5) hole for the bolt torn.

TABLE XVI.—*Series No. VIIb. Single-riveted Lap-joint with three Wrought-iron Rivets of 19 Millimetres Diameter, as in Fig. 39.*

Wrought-iron rivets.

Uncaulked.

Riveting heat, light red.

Manner of riveting, hydraulic.

Maker of joint, F.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with wrought-iron rivets, 29,160 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9700 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.													$P: 3\frac{d^2\pi}{4}$  Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
1	0	...	0	...	0	...	...	...	...	...	0	...	118
2	0	...	0	...	0	...	...	...	...	...	0	...	236
3	0	...	0	...	0	...	...	...	...	...	0	...	354
4	0	...	0	...	0	...	...	...	...	...	0	...	472
5	0	...	0	...	0	...	...	...	...	...	0	...	590
6	0	0	0	0	0.5	0	...	...	...	...	0.2	0	708
7	0	...	0	...	1	...	...	...	...	...	0.3	...	826
8	0.5	0	0	0	1.5	0.5	...	...	...	...	0.7	0.2	944
10	1.5	1	0	0	3	2	...	...	...	...	1.5	1	1180
12	3	2	2.5	2	6	5	...	...	...	...	3.8	3	1416
14	8.5	7	8	7	12.5	11	...	...	...	...	9.7	8.3	1652
16	15	13	30	23	28.5	21.5	...	...	...	...	24.5	19.2	1888
18	33.5	27	...	...	5.9	40.5	...	...	...	...	46.3	33.8	2120

Breaking load in tons—Test No. (1) 29.380; (2) 28.840; (3) 29.260; average, 29.160;  $P: 3\frac{d^2\pi}{4} = 3430$  kilogrammes.

Manner of breaking—Tests Nos. (1), (2), and (3) two rivets sheared.

TABLE XVII.—*Series No. VIIA. Single-riveted Lap-joint with three Nickel-steel Rivets of 25 Millimetres Diameter, as in Fig. 40.*

Kind of nickel steel, A.

Uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 18 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 93,940 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 40,440 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9800 kilogrammes.

Load, P Tons.	Slip in $\frac{1}{100}$ Millimetre.												$P : 3 \frac{d^2 \pi}{4}$  Kilogrammes.
	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
2	0	0	0	0	0	0	0	0	0	0	0	0	136
5	0	0	2	0	1.5	1.5	0	0	1	0	0.9	0.3	340
8	1.5	0	7.5	3.5	6	4.5	3	2.5	2.5	1	4.1	2.3	545
11	3.5	0	12	5	10	7	7	5	5	3.5	7.5	4.1	748
14	7.5	0	16.5	7	13	8	11.5	5	7.5	5	11.2	5.0	953
17	10.5	6.5	21.5	9.5	16.5	9.5	16	7	11	7	15.1	7.9	1100
20	14.5	8	23.5	11.5	19.5	10.5	20.5	8.5	13.5	9	18.3	9.5	1360
25	19.5	9.5	24	15	25	12.5	26	10.5	18.5	11	22.6	11.7	1700
30	25.5	12.5	31	18.5	29.5	14	32	12	23	12.5	23.2	13.9	2040
35	31	14	...	...	34	17	38	16	28	...	32.8	15.7	2380

Breaking load in tons—Test No. (1) 92.000; (2) 94.000; (3) 94.700; (4) 91.980;

(5) 97.000; average, 93,940;  $P : 3 \frac{d^2 \pi}{4} = 6380$  kilogrammes.

Manner of breaking—Test No. (1) plate tore between rivet-hole and edge of plate; (2), (3), and (4) two rivets sheared; (5) three rivets sheared.

C.S.M. (1909)

TABLE XVIII.—*Series No. VIIb. Single-riveted Lap-joint with three Nickel-steel Rivets of 25 Millimetres Diameter, as in Fig. 40.*

Kind of nickel steel, C.

Uncaulked.

Riveting heat, light red.

Manner of riveting, hydraulic.

Maker of joint, F.

Thickness of plate, 18 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 71,170 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 44,010 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9800 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P:3\frac{d^2\pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
2	0	...	0	...	0	...	...	...	...	...	0	...	136	
5	3	2	4	2	7.5	6.5	...	...	...	...	4.8	3.5	340	
8	7	5	8	3.5	8	7	...	...	...	...	7.7	5.2	545	
11	11	7	12.5	6.5	10	8	...	...	...	...	11.2	7.2	748	
14	13.5	10	16	8.5	15	10	...	...	...	...	14.8	9.5	953	
17	20	12.5	20.5	10	19	12	...	...	...	...	19.8	11.5	1160	
20	24	15.5	23.5	11.5	23	14	...	...	...	...	23.5	13.7	1360	
25	31.5	20.5	29	14	31	18	...	...	...	...	30.5	17.5	1700	
30	39.5	27	35	17.5	35	22	...	...	...	...	36.5	22.2	2040	

Breaking load in tons—Test No. (1) 70.000; (2) 63.710; (3) 79.800; average, 71.170;  $P:3\frac{d^2\pi}{4}=4860$  kilogrammes,

Manner of breaking—Tests No. (1) and (2) three rivet-heads broken off; (3) one rivet-head broken off.

TABLE XIX.—*Series No. VIIIc. Single-riveted Lap-joint, with three Nickel-steel Rivets of 25 Millimetres Diameter, as in Fig. 40.*

Kind of nickel steel, A.

Uncaulked.

Riveting heat, light red.

Manner of riveting, pneumatic press.

Maker of joint, G.

Thickness of plate, 18 millimetres.

Snap on head, snap removed just when rivet finished. The firm usually removes the snap 20 seconds after finishing the rivet.

Average ultimate strength of the joint with nickel-steel rivets, 95,670 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 41,010 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9800 kilogrammes.

(When the snap rests for a longer period of time on the rivet-head, the slipping begins later.)

Load, P Tons.	Slip in $\frac{1}{100}$ Millimetre.												$P : 3 \frac{d^2 \pi}{4}$ Kilogrammes.
	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
2	0	...	1	...	0	...	...	...	...	...	0.3	...	136
5	1.5	0	5.5	3	4.5	1	...	...	...	...	3.8	1.3	340
8	4.5	2	9.5	5	8	2	...	...	...	...	7.3	3.0	545
11	9.5	7	13	6	13	3.5	...	...	...	...	11.8	5.5	748
14	14.5	9	16	7	16	5	...	...	...	...	15.5	7.0	953
17	19	...	18.5	8	19.5	7	...	...	...	...	19.0	7.5	1160
20	24.5	...	21.5	8.5	23	8.5	...	...	...	...	23.0	8.5	1360
25	30	...	25	9.5	28	11	...	...	...	...	27.7	10.3	1700
30	36	...	29.5	11	33.5	13	...	...	...	...	33.0	12.0	2040

Breaking load in tons—Test No. (1) 94.580; (2) 97.000; (3) 95.440; average,

95.670;  $P : 3 \frac{d^2 \pi}{4} = 6510$  kilogrammes.

Manner of breaking—Test No. (1) head of one rivet off; (2) three rivets sheared; (3) two rivets sheared.



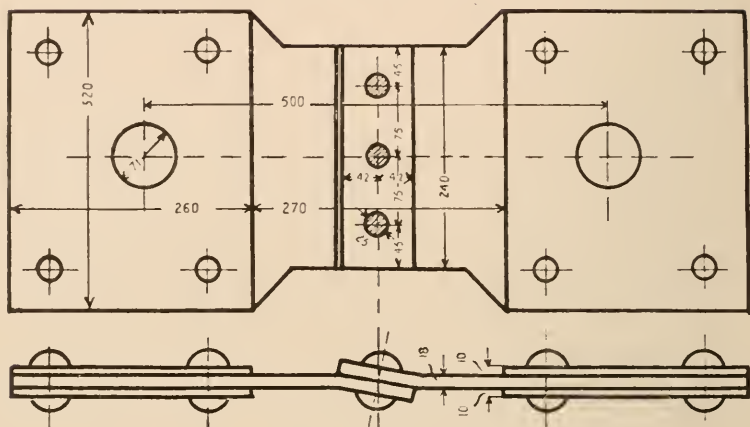


FIG. 40.



FIG. 41.—Series IX.

TABLE XX.—*Series No. IX. Double-riveted Lap-joint, with five Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 42.*

Kind of nickel steel, D.

Uncaulked.

Riveting heat, light red.

Manner of riveting, electro-hydraulic.

Maker of joint, E.

Thickness of plate, 12 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 99,560 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 44,810 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 9600 kilogrammes.

Load, P Tons.	Slip in $\frac{1}{100}$ Millimetre.												$P: 3\frac{d^2\pi}{4}$  Kilogrammes.
	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic Per Cent.	Permanent. Per Cent.	
2	0	...	0	...	0	...	0.5	...	1	...	0.3	...	141
5	6	5	6	4	5	3.5	4	2	5.5	4.5	5.3	3.8	352
8	11.5	8	9.5	6	12	9.5	8.5	5	10.5	7.5	10.4	7.2	564
11	16.5	10.5	12	6.5	17	12.5	11.5	7	14.5	9.5	14.3	9.2	774
14	19	11	13.5	8	20	14.5	14	8	17.5	11	16.8	10.5	987
17	23	17	15.5	8	23.5	15.5	16.5	9.5	20.5	12	19.8	12.4	1190
20	26	18	17.5	9	26.5	17	19	9.5	23	13	22.4	13.3	1410
25	30	19	20	10.5	31	17.5	22	11	27	15	26.0	14.6	1760
30	30	20	23	11.5	34.5	19.5	25	12.5	30	17.5	28.5	16.2	2110

Breaking load in tons—Test No. (1) 99.700; (2) 101.260; (3) 101.120; (4) 99.000;

(5) 96.700; average, 99.560;  $P: 3\frac{d^2\pi}{4} = 7020$  kilogrammes.

Manner of breaking—Test No. (1) four rivet-heads pulled through the plates; (2) and (5) five rivet-heads pulled through the plates; (3) three rivet-heads pulled through the plates; (4) plate broken between two rivets.

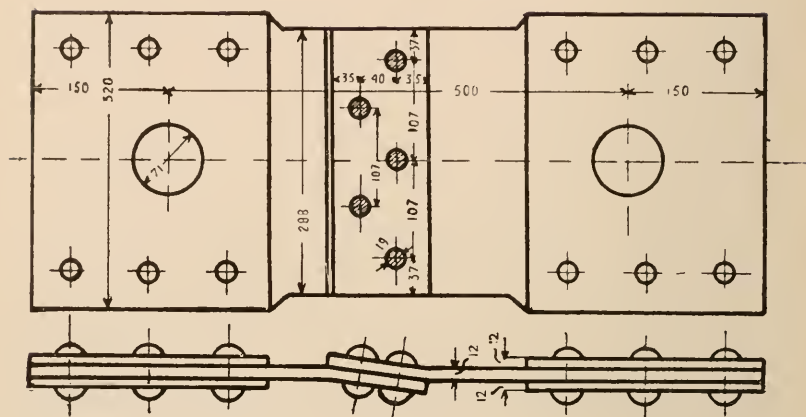


FIG. 42.

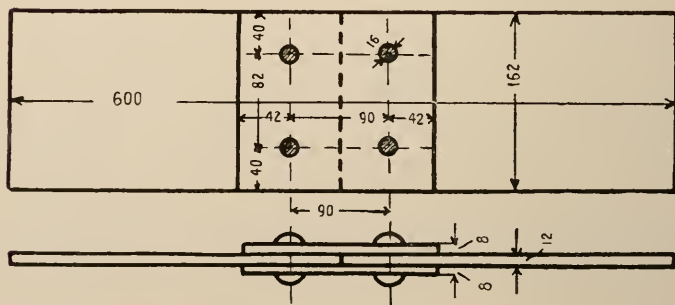


FIG. 43.

TABLE XXI.—*Series No. Xa. Single-riveted Butt-joint, with four Nickel-steel Rivets of 16 Millimetres Diameter, as in Fig. 43.*

Kind of nickel steel, C.

Uncaulked.

Riveting heat, light red.

Manner of riveting, hydraulic.

Maker of joint, F.

Thickness of plate, 12 millimetres.

Thickness of cover straps, 8 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 40,000 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 28,100 kilogrammes.

Load, P Tons.	Slip in $\frac{1}{100}$ Millimetre.												$P : 4 \frac{d^2 \pi}{4}$ Kilogrammes.
	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
2	3	...	3.5	...	2	...	...	...	...	...	2.8	...	249
3	5.5	...	5.5	...	5	...	...	...	...	...	5.3	...	374
4	8	...	7.5	...	7.5	...	...	...	...	...	7.7	...	498
5	10	...	10	...	10	...	...	...	...	...	10	...	622
6	12	5.5	12.5	5.5	12.5	6	...	...	...	...	12.3	5.7	747
7	14	...	13.5	...	15.5	...	...	...	...	...	14.3	...	871
8	16.5	7.5	15	6	18	8	...	...	...	...	16.5	7.2	994
10	21.5	9	19	7	23.5	10.5	...	...	...	...	21.3	8.8	1240
12	25	10	23	8	29.5	14	...	...	...	...	25.8	10.7	1490
14	28.5	11.5	29.5	11	37.5	20	...	...	...	...	31.8	14.2	1740
16	36.5	18	33	12.5	43	22	...	...	...	...	37.5	17.3	1990

Breaking load in tons—Test No. (1) 34.500; (2) 41.600; (3) 43.890; average, 40.000;  $P : 4 \frac{d^2 \pi}{4} = 4980$  kilogrammes.

Manner of breaking—Test No. (1), one rivet-shank broken in middle; (2 and 3), rivet-holes sheared out.

TABLE XXII.—*Series Ab. Single-riveted Butt-joint, with four Nickel-steel Rivets of 16 Millimetres Diameter, as in Fig. 43.*

Kind of nickel steel, D.

Uncaulked.

Riveting heat, light red.

Manner of riveting, pneumatic hammer.

Maker of joint, H.

Thickness of plate, 12 millimetres.

Thickness of cover straps, 8 millimetres.

Average ultimate strength of the joint with nickel-steel rivets, 41,330 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 28,100 kilogrammes.

Load, P Tons		Slip in $\frac{1}{100}$ Millimetre.														$P: 4 \frac{d^2 \pi}{4}$ Kilogrammes.	
		Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.					
		Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.				
2	1	...	1.5	...	0	...	...	...	...	...	0.8	...	249				
3	3	...	5	...	2	...	...	...	...	...	3.3	...	374				
4	5	...	8	...	3.5	...	...	...	...	...	5.5	...	498				
5	7.5	...	11.5	...	4.5	...	...	...	...	...	7.8	...	622				
6	9.5	7	14	10.5	7	5	...	...	...	...	10.2	7.5	747				
7	12	...	17	...	9	...	...	...	...	...	12.7	...	871				
8	14	10	20	14.5	11.5	7.5	...	...	...	...	15.2	10.7	994				
10	18	11.5	25	18	16	11.5	...	...	...	...	19.7	13.7	1240				
12	23.5	16	32	22.5	20.5	14	...	...	...	...	25.3	17.5	1490				
14	27	18.5	39	26	25.5	16.5	...	...	...	...	30.5	20.3	1740				
16	38.5	23	46	31	30	19	...	...	...	...	38.2	24.3	1990				

Breaking load in tons—Test No. (1) 40.800; (2) 42.140; (3) 41.060; average,

41.330;  $P: 4 \frac{d^2 \pi}{4} = 5130$  kilogrammes.

Manner of breaking—Tests Nos. 1-3, rivet-holes sheared out.

TABLE XXIII.—*Series No. Xc. Single-riveted Butt-joint, with three Nickel-steel Rivets of 16 Millimetres Diameter, as in Fig. 43.*

Kind of nickel steel, A.

Uncaulked.

Riveting heat, light red.

Manner of riveting, by hand.

Maker of joint, G.

Thickness of plate, 12 millimetres.

Thickness of cover straps, 8 millimetres.

Snap on head, 4-6 seconds, hammered by hand-hammer; 17-33 seconds, by snap-hammer.

Average ultimate strength of the joint with nickel-steel rivets, 41,550 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 28,100 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P : 4 \frac{d^2 \pi}{4}$ Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.	Elastic, Per Cent.	Permanent, Per Cent.		
2	0	...	1	...	0	...	...	...	...	...	0.3	...	249	
3	1	...	2.5	...	1	...	...	...	...	...	1.5	...	374	
4	2.5	...	3	...	1	...	...	...	...	...	2.2	...	498	
5	5	...	4.5	...	2.5	...	...	...	...	...	4.0	...	622	
6	6	5	6	3.5	4.5	2.5	...	...	...	...	5.5	3.7	747	
7	9.5	...	7.5	...	7	...	...	...	...	...	8.0	...	871	
8	12	8.5	9.5	5.5	9	7	...	...	...	...	10.2	7.0	994	
10	17.5	12.5	13	7.5	15	11	...	...	...	...	15.2	10.3	1240	
12	20	15	17	9.5	21	15.5	...	...	...	...	19.3	13.3	1490	
14	22	17	22	13	26.5	19.5	...	...	...	...	23.5	16.5	1740	
16	35	29	26	15.5	33	23.5	...	...	...	...	31.3	22.7	1990	

Breaking load in tons—Test No. (1) 35.000; (2) 44.850; (3) 44.790; average, 41.550;  $P : 4 \frac{d^2 \pi}{4} = 5170$  kilogrammes.

Manner of breaking—Test No. (1), one rivet sheared; (2 and 3), one rivet-hole sheared out.



TABLE XXIV.—*Series No. XIa. Single-riveted Butt-joint, with four Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 44.*

Kind of nickel steel, A.

Uncaulked.

Riveting heat, light red.

Manner of riveting, hydraulic.

Maker of joint, F.

Thickness of plate, 14 millimetres.

Thickness of cover straps, 9 millimetres.

Snap on head, normal.

Average ultimate strength of the joint with nickel-steel rivets, 62,760 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 39,700 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 12,600 kilogrammes.

Load, P Tons.	Slip in $\frac{1}{100}$ Millimetre.												$P : 4 \frac{d^2 \pi}{4}$  Kilogrammes.
	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.		
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	
2	1.5	...	1	...	1	...	...	...	...	...	1.2	...	175
3	3.5	...	2.5	...	2.5	...	...	...	...	...	2.8	...	263
4	5	...	4.5	...	4	...	...	...	...	...	4.5	...	350
5	6.5	...	6	...	5.5	...	...	...	...	...	6	...	437
6	8	4.5	8	4.5	6.5	3.5	...	...	...	...	7.5	4.2	525
7	10	...	9.5	...	8.5	...	...	...	...	...	9.3	...	615
8	11.5	5	11.5	6	10.5	5.5	...	...	...	...	11.2	5.5	700
10	14.5	6	14	7.5	13.5	7	...	...	...	...	14.0	6.8	875
12	17.5	6.5	18	9	16.5	8.5	...	...	...	...	17.3	8.0	1050
14	20.5	7.5	22.5	11.5	20.5	9.5	...	...	...	...	21.2	9.5	1230
16	24	8	26.5	12.5	24	11	...	...	...	...	24.8	10.5	1400
18	27	9	32	14	27.5	12.5	...	...	...	...	28.8	11.8	1580
20	30	11	35.5	17	31.5	14.5	...	...	...	...	32.3	14.2	1750

Breaking load in tons—Test No. (1) 61.380; (2) 62.510; (3) 63.380; average,

 $62.760$ ;  $P : 4 \frac{d^2 \pi}{4} = 5500$  kilogrammes.

Manner of breaking—Tests Nos. 1-3, rivet-holes sheared out.



TABLE XXV.—*Series No. XIb. Single-riveted Butt-joint, with four Nickel-steel Rivets of 19 Millimetres Diameter, as in Fig. 44.*

Kind of nickel steel, D.

Uncaulked.

Riveting heat, light red.

Manner of riveting, pneumatic hammer.

Maker of joint, II.

Thickness of plate, 14 millimetres.

Thickness of cover strap, 9 millimetres.

Average ultimate strength of the joint with nickel-steel rivets, 59,740 kilogrammes.

Average ultimate strength of the same joint with wrought-iron or mild-steel rivets, 39,700 kilogrammes.

Beginning of slip when wrought-iron rivets are used, according to von Bach, 12,600 kilogrammes.

Slip in $\frac{1}{100}$ Millimetre.														$P : 3 \frac{d^2 \pi}{4}$  Kilogrammes.
Load, P Tons.	Test No. 1.		Test No. 2.		Test No. 3.		Test No. 4.		Test No. 5.		Average.			
	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.	Elastic. Per Cent.	Permanent. Per Cent.		
2	0	...	1.5	...	2	...	...	...	...	...	1.2	...	175	
3	4.5	...	3.5	...	6	...	...	...	...	...	4.7	...	263	
4	8.5	...	7	...	9.5	...	...	...	...	...	8.3	...	350	
5	12	...	10	...	13	...	...	...	...	...	11.7	...	437	
6	15.5	13	12.5	9.5	15.5	13	...	...	...	...	14.5	11.8	525	
7	19	...	15.5	...	18.5	...	...	...	...	...	17.7	...	615	
8	22	18	18	12.5	21	16	...	...	...	...	20.3	15.5	700	
10	27.5	22	23	16	26	19	...	...	...	...	25.5	19.0	875	
12	34.5	26.5	28	19	31	21.5	...	...	...	...	31.5	22.3	1050	
14	39	28.5	32	21	36.5	24.5	...	...	...	...	35.8	24.7	1230	
16	42.5	31.5	37	23.5	42	28.5	...	...	...	...	40.5	27.8	1400	
18	48.5	34.5	43.5	28	47	31	...	...	...	...	46.3	31.2	1580	
20	55.5	39	50.5	32.5	54.5	36.5	...	...	...	...	53.5	36.0	1750	

Breaking load in tons—Test No. (1) 66,420; (2) 54,800; (3) 58,000; average,

59,740;  $P : 3 \frac{d^2 \pi}{4} = 5230$  kilogrammes.Manner of breaking—Test No. (1), plate broken; (2), rivet-holes sheared out;  
(3) one rivet-hole sheared out.

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### III.

## THE PREPARATION OF CARBON-FREE FERRO-MANGANESE.

(FURTHER EXPERIMENTS.)

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#### INTRODUCTION.

THE first paper submitted by Mr. E. G. Ll. Roberts and the author to this Institute dealt mainly with the attempted preparation of carbon-free ferro-manganese from the commercial alloy. The conclusion reached was that the only process practically possible, on a commercial scale, was the fusion of ferro-manganese at a high temperature ( $1600^{\circ}$  to  $1700^{\circ}$  C. approximate), in a basic-lined furnace with a fluid slag saturated with  $\text{MnO}$ . Owing to various difficulties it has not been possible to carry out the operations intended on a large scale in a magnesite lined open-hearth furnace; this paper therefore briefly embodies a series of experiments carried out in the laboratories of the Royal School of Mines, with the object of obtaining a carbon-free metal.

A number of these experiments are of scientific interest only, and not economically possible; but as the field of research in this direction is, comparatively speaking, unexplored, it may not be out of place to include them in this paper.

The original work carried out in conjunction with Mr. Roberts, embraced practically every possible method for preparing the carbon-free alloy from ordinary ferro-manganese and left very little scope for further work in this direction.

Very numerous experiments were carried out in order to re-



move or replace the carbon. They may be briefly summarised as follows:—

1. Replacement of combined carbon by silicon and aluminium.
2. Prolonged cementation in various oxides.
3. Bessemerisation of the alloy.
4. Fusion at a high temperature with metallic oxides.

The work since carried out by the author has been in two main directions: firstly, and in continuation of previous experiments endeavouring to decarburise ordinary ferro-manganese; secondly, attempting to obtain the carbon-free metal from its ore. It will be convenient to study this work from these two points of view, which may be embodied under the following titles:—

1. "The Decarburisation of Ferro-manganese."
2. "The Production of Carbon-free Manganese from its Ore."

#### DECARBURISATION—FUSION WITH MANGANESE DIOXIDE.

From previously published results it will be seen that this method afforded the most hopeful possibility of obtaining the pure alloy, and accordingly ferro-manganese was crushed to pass a 90 sieve, mixed with (*a*) 30 per cent. and (*b*) 40 per cent. of manganese dioxide in powder, melted and kept fluid for three hours at a temperature varying between 1600° and 1700° C. as nearly as could be regulated. The crucibles were bauxite-lined salamanders and were only just penetrated by the very pasty slag which had formed. The composition of the resulting metal in each case is shown by the following analyses:—

	Original Metal.	A. 30 per Cent. MnO <sub>2</sub> .	B. 40 per Cent. MnO <sub>2</sub> .
	Per Cent.	Per Cent.	Per Cent.
Manganese . . . .	80.15	73.53	71.00
Iron . . . . .	12.00	19.31	21.67
Silicon . . . . .	0.74	0.23	0.14
Carbon (total) . . .	6.68	6.53	6.81
Sulphur . . . . .	traces	...	...
Phosphorus and arsenic	0.28	...	...

The amount of  $\text{MnO}_2$  employed in the above fusions is considerably in excess of the quantity theoretically required.

As soon as the exterior of the crucibles became a dull red the contents glowed throughout, doubtless due to oxidation of the manganese. The loss of metal was very considerable, amounting to exactly 30 per cent. in the first case and 43 per cent. in the second.

It is quite evident from these two fusions, since the metal was intimately mixed with manganese dioxide and both passed through a 90 sieve, that decarburisation by this method in the laboratory, if not on a commercial scale, is impossible. Further attempts with  $\text{MnO}_2$  were therefore abandoned.

#### VOLATILISATION OF MANGANESE.

In the above and subsequent experiments it was not always possible to collect and weigh the slag formed. Fusions were therefore made to discover if losses occurred through volatilisation.

Fusions were simultaneously performed for (*a*) three hours, (*b*) four hours, and (*c*) five hours at temperatures, as nearly as could be regulated,  $1300^\circ \text{C.}$ ,  $1400^\circ \text{C.}$ , and  $1600^\circ$  to  $1700^\circ \text{C.}$  respectively. Salamander crucibles were employed and the lids secured by clay, a small perforation being made just under the cover to allow any gases or volatilised metal to escape. No loss in any of the fusions was apparent; in fact the final weight of the metal was in every case slightly greater than that taken, due doubtless to silicon absorption from the crucible.

Temperature and Time of Fusion.		Increase in Weight.	Silicon Content. Original Metal = 0.74 per Cent.
Degrees C.	Hours.	Per Cent.	Per Cent.
1300	3	0.5	...
1300	4	1.2	...
1300	5	1.75	1.86 ( <i>a</i> )
1400	5	2.5	3.13
1600-1700	5	3.0	4.00 ( <i>b</i> )

Analyses of (*a*) and (*b*) show how the composition of the metal had been affected.

	Original Metal.	<i>a.</i>	<i>b.</i>
	Per Cent.	Per Cent.	Per Cent.
Manganese . . .	80.15	78.00	75.4
Iron . . . . .	12.00	13.20	14.0
Silicon . . . . .	0.74	1.86	4.00
Carbon (total) . .	6.68	6.60	6.24

The increase in the percentage of silicon and the decrease of the carbon emphasises the fact pointed out in a previous paper, that absorption of silicon is always attended with loss of carbon.

Ten pounds of ferro-manganese were then melted in a large open graphite crucible and maintained at a white heat in a wind furnace for five hours. A considerable amount of slag formed during that time, but the metal only decreased very slightly in weight. Allowing for the manganese present in the slag, the net result was a gain of 3 per cent. Conclusive proofs are thus afforded that manganese is non-volatile, and therefore certain statements made by several authors, calling attention to the volatility of that metal at temperatures existing in metallurgical furnaces, can only be regarded as inaccurate. Probably the true explanation is that the metal is very readily oxidised, and the oxide lost either mechanically or in the slag during metallurgical operations.

#### FUSION WITH ZINC AND COPPER OXIDES.

The next series of experiments was carried out with the fused metal in contact with zinc and copper oxides—compounds easily reduced by carbon.

The theoretical quantity of black oxide of copper necessary to remove the carbon was intimately mixed with finely crushed ferro-manganese, melted in a bauxite-lined crucible and kept fluid for three hours. On cooling, a highly crystalline mass of metal separated beneath a layer of metal which appeared to be ferro-manganese of the ordinary composition. Analysis showed that the upper portion was not very different from the original alloy, the carbon content, however, having slightly

decreased; but the lower portion was a copper manganese alloy which contained no carbon, and had absorbed silicon to the extent of 2 per cent.

	Top.	Bottom.
	Per Cent.	Per Cent.
Manganese . . . . .	77.00	33.20
Copper . . . . .	traces	60.39
Iron . . . . .	15.62	4.38
Silicon . . . . .	1.17	2.01
Carbon . . . . .	6.16	nil

The fusion was repeated with double the amount of copper oxide, with a similar result, the only difference being a considerable increase in the quantity of the copper manganese alloy (containing 65.2 per cent. copper) and a further reduction of the carbon content, viz. from 6.7 per cent. to 5.83 per cent. in the ferro-manganese.

Zinc oxide was now substituted for CuO and two meltings performed at a very high temperature, the first for a period of two hours and the second four hours.

The second fusion was made under a cover of manganese dioxide. The contents of the crucibles were allowed to solidify, and broken out when cold. In both cases a large quantity of graphite had separated and a considerable amount of slag formed; no carbon had been relatively removed, but the manganese content had considerably decreased, especially in the first case, when the metal lost no less than 25 per cent. of its weight. Analysis:

	Original.	Time of Fusion with ZnO.	
		2 Hours.	4 Hours.
	Per Cent.	Per Cent.	Per Cent.
Manganese . . . . .	80.15	66.1	74.0
Iron . . . . .	12.00	26.4	19.2
Silicon . . . . .	0.74	0.47	0.65
Carbon . . . . .	6.68	6.66	6.71

It is at once apparent from the results of the experi-

ments described here and in a former paper, that manganese has a much greater affinity for carbon than it has for any other element. The commercial alloy is always saturated with carbon, as the experiment described below definitely proves.

Ferro-manganese was crushed to pass 120 sieve, intimately mixed with twice its own weight of powdered starch and heated in a thick graphite pot for three hours at the highest temperature it was possible to produce in a wind furnace working under forced draught from a Roots blower (approximately  $1775^{\circ}$  C.). Analysis of samples before and after this heating proved that the carbon content had not increased—in fact a slight diminution had taken place.

	Original Sample.	After Fusion.
	Per Cent.	Per Cent.
Manganese . . . . .	80.15	78.8
Iron . . . . .	12.00	12.8
Carbon . . . . .	6.68	6.64
Silicon . . . . .	0.74	1.35

The conditions were eminently favourable for carbon absorption, but this did not take place. The slight lowering of the carbon content is undoubtedly due to silicon.

In endeavouring to decarburise ferro-manganese, the following agents have been employed, either in fusion, cementation, or both: Oxides, viz. manganese dioxide or pyrolusite, ferric oxide (hæmatite), silica, barium peroxide, alumina, zinc and copper oxides, lime, magnesia and titanite oxide, also ferrous and manganous carbonates (for FeO and MnO); the gases hydrogen, oxygen, and carbon dioxide; and the metals calcium and aluminium. Most of these failed to give any satisfactory reduction of the carbon content of the alloy, and even when the carbon was lowered the process was in no case commercially practicable. The experiments now to be described have been carried out with a view to determine the possibility of producing pure manganese from its ore.

### THE PREPARATION OF CARBON-FREE MANGANESE FROM ITS ORE—REDUCTION BY CARBONACEOUS MATERIALS.

The first experiments were on lines similar to the production of metallic nickel from its oxide; flour, sugar, or other similar material which yields carbon on heating, being intimately mixed with manganese oxide and the reduction carried out at a red heat.

Sugar, in such proportion that not quite sufficient carbon would be present to reduce all the manganese, was mixed with manganese dioxide and a little water, and the paste dried and strongly heated in a clay crucible. The result was entirely slag, no metal whatever being produced. The experiment was repeated under somewhat different conditions; the mixture, which now contained theoretically sufficient sugar to reduce all the manganese, was cut into cubes, dried and heated in a closed iron tube at a temperature of  $850^{\circ}$  to  $900^{\circ}$  C.

The cubes on cooling looked somewhat metallic, and were melted. A small amount of metal resulted, but of the following composition:—

	Per Cent.
Manganese . . . . .	1.4
Iron . . . . .	94.5
Carbon . . . . .	2.9
Silicon . . . . .	0.7

The manganese dioxide employed contained:—

	Per Cent.
Manganese dioxide . . . . .	86.8
Iron oxide . . . . .	3.4
Silica . . . . .	9.3

The mixture with sugar was not at all satisfactory, the material failing to dry well. Starch was accordingly substituted as the reducing agent and gave a very satisfactory mixture, which when dried yielded hard cubes capable of being handled without breaking or crumbling.

Reductions were performed in a closed iron tube as before, the manganese dioxide being mixed with 10 per cent., 20 per cent., 30 per cent., 50 per cent., and lastly an equal weight



of starch. The temperature of reduction as shown by the Roberts-Austen pyrometer was  $865^{\circ}\text{C}$ .

On fusing, the results given in the following table were obtained:—

Amount of Starch Employed.				
10 per Cent.	20 per Cent.	30 per Cent.	50 per Cent.	100 per Cent.
Cubes disintegrated. Mixed green and brown oxides resulted on cooling.	Cubes retained shape. Apparently entirely composed of green manganous oxide.	Cubes retained shape. Colour almost black. Very small amount of green oxide present.	Cubes retained shape. No green oxide present. Colour quite black.	
Slag only.	Slag only.	Slag and very small amount of metal.  <i>Composition :</i> Iron, 96.2 per cent. Manganese, 0.34 per cent. Carbon, 2.9 per cent.	Slag and small amount of metal (yield 8 per cent.).  <i>Composition :</i> Iron, 27.6 per cent. Manganese, 67.4 per cent. Carbon, 4.42 per cent. Silicon, 0.54 per cent.	Slag with more metal (yield, 19 per cent.).  <i>Composition :</i> Iron, 13.9 per cent. Manganese, 80.8 per cent. Carbon, 5.0 per cent. Silicon, 0.3 per cent.

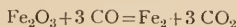
Experiments were now conducted in order to investigate the possibility of gaseous reduction of the ore.

A suggestion was made to the author by M. Bourcoud, of Bilbao, Spain, a well-known authority on gas problems, to the effect that there was a period of overlap between the reduction of manganese ore to the metal by carbon and the absorption of that element. Further, if the ore could be heated in an atmosphere of carbon monoxide to about  $1100^{\circ}\text{C}$ . with carbon, but in insufficient quantity to reduce the whole of the ore, a carbonless metal would probably result.

#### CARBON MONOXIDE REDUCTION.

An investigation was first made to study the behaviour of manganese ore under the action of carbon monoxide alone.

It has long been an established fact that in the upper zones of iron blast-furnaces, iron ore is reduced by CO in accordance with the equation



and from analogy it might be expected that a similar result would be obtained with manganese ore.

The experiment was carried out in the following manner:—A wrought-iron tube, 3 inches in diameter and 2 feet 6 inches in length, was loosely filled for about 2 feet of its length with small pieces of pyrolusite. This tube was heated in a large coke-fired wind furnace, and maintained at  $1100^\circ \text{C}$ . (as nearly as could be regulated). The temperature was controlled by means of the Roberts-Austen pyrometer, the thermo-couple being passed down a length of small-bore gas barrel attached for that purpose to the large tube. Carbon monoxide prepared by passing carbon dioxide from a cylinder containing the liquefied gas through an iron tube, 2 feet in length and  $1\frac{1}{2}$  inch in diameter, filled with red-hot charcoal, was led directly into the large tube containing the pyrolusite. The experiment was continued for just over nine hours, with the result that green manganous oxide only and no manganese was produced, proving beyond a doubt that CO is without action on manganous oxide. Under the action of carbon monoxide,  $\text{MnO}_2$  (pyrolusite) is rapidly reduced to  $\text{MnO}$ , and this was easily observed by the character of the issuing gas from the exit tube of the cylinder containing the heated ore. At first the gas was practically all  $\text{CO}_2$ , which gradually gave place to CO as more and more of the manganese dioxide became monoxide. Ultimately the issuing gas burnt with a steady pale flame for about three hours. The charcoal in the smaller tube was frequently renewed, a screw plug being fitted to it for that purpose. An experiment on the lines suggested by M. Bourcoud was next performed, the arrangements being practically the same as before.

Pyrolusite dried and mixed with one-eighth of its weight of charcoal was placed in a similar 3-inch tube. As both ore and charcoal had been crushed to pass a  $\frac{1}{4}$ -inch sieve a few pieces of fire-brick were placed at the bottom of this tube to

allow a free passage for the gas. Carbon monoxide was passed exactly in the same manner as before. Six and a half hours were occupied in this investigation, and 35 lbs. of  $\text{CO}_2$  were consumed during that time.

The tubes were removed from the furnace and allowed to cool overnight. On opening the large tube, the contents were

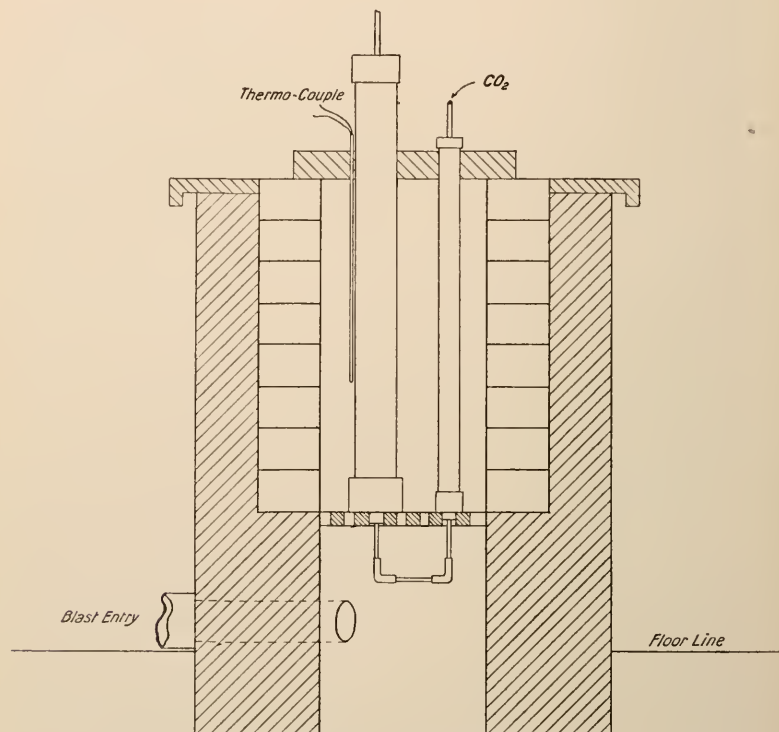
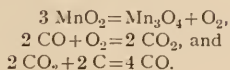


FIG. 1.—Section of Forced-draught Furnace.

found to be of a very dark colour and to some extent fritted together; no charcoal was present, and the ore had lost 16 per cent. by weight. The material did not appear to be at all metallic, and on melting a portion no metal whatever was obtained, the mass consisting largely of  $\text{Mn}_3\text{O}_4$ .

The consumption of the charcoal may have been due to free

oxygen evolved from the manganese dioxide, and possibly to the joint action of CO and O thus:—



During the whole time the experiment was conducted, CO was burning at the top of the reduction tube.

### REDUCTION BY COAL GAS.

Coal gas as the reducing agent was next tried under similar conditions; the gas, however, was not previously heated, but led direct from the main. An iron tube of somewhat smaller diameter was employed, and in this the manganese ore occupied a depth of 2 feet.

The gas acted upon the oxide for a period of eight hours, when the experiment had to be discontinued on account of the cylinder becoming distorted under the long-continued heat at approximately  $1200^\circ \text{C}$ . During the last stages of reduction the temperature probably reached  $1500^\circ \text{C}$ .

When cold the tube was sawn longitudinally, which revealed a few inches of metal at the bottom having the appearance of only just having been melted. (The tube was much thinner at the lower half of its length and much of the metal must have been derived from this source.) The next 6 inches or so contained 31 per cent. of metal entangled in a semi-fused mass of dark-coloured oxide. Above this much green manganous oxide was present, showing here and there small masses of metal. The top and unheated part of the tube was almost entirely filled with unreduced ore.

Analysis of the metal from different parts of the tube showed:—

	Bottom.	Higher Portions.	
	Per Cent.	Per Cent.	
Manganese . . .	1·8	58·4	82·0
Iron . . . .	94·4	33·4	10·6
Carbon . . . .	3·20	6·85	7·14
Silicon . . . .	0·62	1·16	0·12

The metal at the bottom of the tube was coated with graphite and had a brilliant black surface.

Much water was given off from the exit tube, and the flame of the issuing gas was pale and almost non-luminous, showing CO had been formed.

As this experiment from the point of view of reduction was fairly successful, and as the resulting alloy contained about 7 per cent. of carbon, it seemed probable that if water gas were substituted for coal gas an effective method for producing carbonless ferro-manganese or manganese on a commercial scale would be discovered. In order to obtain data for such a method of preparation, hydrogen was therefore the next reducing agent tried.

### HYDROGEN REDUCTION.

The experiments in this case were conducted on a much smaller scale, the hydrogen gas being passed over small quantities of ore at different temperatures for various lengths of time. The ore was contained in porcelain boats, and the results of the first attempted reductions are tabulated below :

No.	Tempe ature.	Time.	Result.
	Degrees C.	Hours.	
1	730	$\frac{1}{2}$	In every case after about three minutes the ore began to change colour, water was given off, and the oxide gradually became a bright green colour throughout, no further change taking place.
2	730	2	
3	850	$\frac{1}{2}$	
4	950	$\frac{1}{2}$	
5	950	2	
6	1150	...	

Nos. 1, 2, 3, 4, and 5 were conducted in a large silica tube heated in an electric furnace, and No. 6 was performed in a gas muffle in a porcelain tube. The temperatures were recorded by the thermo-couple pyrometer, and are given in round numbers, the limit of error being  $\pm 10^{\circ}$  C.

A wrought-iron tube was next substituted and heating effected in a Fletcher furnace, where the temperature could be easily regulated and the tube maintained at a constant and uniform heat for some length of time.

At 1100° C., 1200° C., and 1300° C., hydrogen being passed in each case for two hours, green oxide was again produced, but contained small particles of metal which, on analysis, proved to be iron with entangled manganous oxide. One small sample gave 69·4 per cent. iron with 28·9 per cent. MnO.

The pyrolusite used in these investigations had an average composition :

	Per Cent.
Manganese dioxide . . . . .	85·2
Iron oxide . . . . .	13·3
Silica . . . . .	0·3

When the iron tube containing the oxide was maintained at a temperature near its melting point (mean pyrometer record 1480° C.), green oxide was again produced, together with a small mass of metal which contained 93·7 per cent. iron and 4·8 per cent. manganese.

A further experiment was conducted under exactly similar conditions, but specially selected ore was utilised, with the result that the entire mass consisted of mixed green and brown oxide, with only a trace of metal.

The results of these investigations are rather extraordinary, and prove beyond doubt that the reduction of the metal by coal gas was entirely due to hydrocarbons or deposited carbon.

All hopes of producing a carbonless metal or alloy on these lines had therefore to be abandoned.

A somewhat curious effect was produced upon the iron tubes which held the ore, the manganese content being raised after heating to an average of 0·23 per cent. at the top and 0·35 per cent. at the bottom.

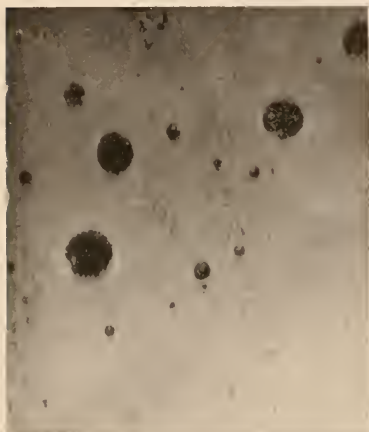
The tube, after the last experiment, was cut or filed as shown, and the metal analysed.

In the original tube, before heating, 0·037 per cent. manganese was present, and the cuttings or filings contained respectively :

	Manganese. Per Cent.
(a) . . . . .	0·23
(b) . . . . .	0·35
(c) . . . . .	0·075
(d) . . . . .	0·16
(e) . . . . .	0·20



(*a*) and (*b*) were well hammered and rolled out to remove all adhering slag and oxide.



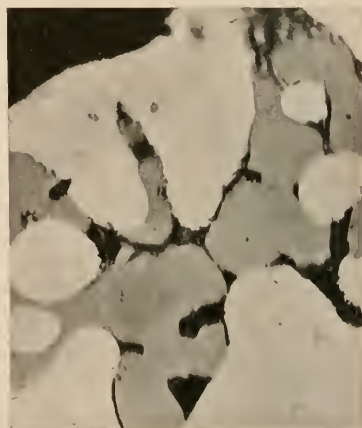
No. 1.—Original tube, quite typical of the whole cross-section surface, showing small slag patches.



No. 2.—Inner edge of the same tube, showing the ferrous silicate coating.



No. 3.—Tube after heating with pyrolusite in interior, showing increased size of slag patches.



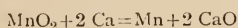
No. 4.—Inner edge of tube, showing penetration of manganese silicate.

Microscopical examination shows that the manganese penetrated in the form of silicate.

Gaseous reductions having been proved a failure, and knowing that aluminium easily reduces metallic manganese from its oxide, metallic substitution was next attempted but without success.

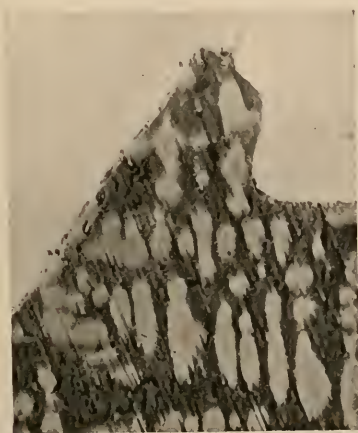
### METALLIC SUBSTITUTION.

Metallic calcium in a fine state of division was mixed in atomic proportions with prepared manganese dioxide in accordance with the equation



and fired.

The result was a most violent action, attended with an exceedingly brilliant flash of light and copious brown fumes. No



No. 5.—Large slag patch in tube after heating, not typical, but many such were present.

metal was obtained and very little slag. The crucible which held the mixture was stained a bright green colour.

A much more violent action resulted when crushed pyrolusite was substituted for prepared  $\text{MnO}_2$ , but again no metallic manganese was produced. Employing twice the amount of calcium, only green manganous oxide and lime were obtained. Zinc was then substituted for calcium, being mixed with both pyrolusite and artificial  $\text{MnO}_2$ , and in both cases only a

mass of brown oxides resulted. The reaction was difficult to start, and the mixture of powdered zinc and manganese dioxide had to be heated before firing with barium peroxide and powdered magnesium. Here again it was noticed that the action was more violent with pyrolusite than with the manufactured oxide.

When placed on a bath of molten zinc, pyrolusite caused rapid oxidation of that metal, green and brown oxides being obtained, which yielded no metal whatever after heating at a very high temperature.

Fusion with iron filings concluded these experiments. Equal parts of pyrolusite and iron filings fused at a white heat resulted in a black oxidised non-metallic mass. With two parts filings and one of ore some metal resulted, but it was apparently mixed with oxide, and did not appear to have been properly melted; it consisted of iron with 2.56 per cent. of manganese, probably as oxide. Employing five parts filings and two of ore, after heating for four hours at the highest possible temperature (about  $1700^{\circ}$  C.) in a fireclay crucible placed in a large salamander crucible with a sand packing, iron was obtained which contained not a trace of manganese. As the filings contained 0.48 per cent. of that metal, it was obviously removed by the action of the ore.

### CONCLUSIONS.

From a consideration of the data in this paper, and in the previous report published in the Journal in 1907, it will be seen that attempted gaseous and metallic reductions of the ore have completely failed; further, as very numerous attempts at the decarburisation of ferro-manganese have proved futile, the author is compelled to believe that the commercial and economical production of the carbon-free alloy is an impossibility.

This failure may be attributed to several facts which have been definitely proved:

1. Manganese has a greater affinity for carbon than for any other element. Evidence of this is shown in almost every experiment that has been described. The only elements that

can replace carbon have been shown to be aluminium and silicon. The use of the former entails heavy expense, and produces an alloy which very rapidly disintegrates; further, only about one part of carbon is removed by the addition of ten parts of aluminium. Silicon, although it replaces carbon to a certain extent, nevertheless soon reaches a limit beyond which it is impossible to further lower the carbon content without enormously increasing the percentage of silicon, in which case a high-grade silico-spiegel is produced instead of carbon-free ferro-manganese.

2. Garrison's statement that, "In the reduction of manganese ore by carbon, carbide and not the metal is invariably produced," is supported by the results of coal-gas reduction of the ore, but this fact requires modification unless it is assumed that carbides other than  $Mn_3C$  exist. This appears to be quite a probable view, for Moissan has produced metallic manganese by carbon reduction of the oxide containing no less than 14.59 per cent. carbon; and if reference be made to the reductions described on p. 153, it will be noticed that the manganese increases with the percentage of carbon employed both in the yield of metal and actual percentage of manganese, at the same time the carbon content also becomes greater, and here insufficient carbon is present to satisfy the formula  $Mn_3C$ .

3. Under oxidising conditions, carbon is only removed from the alloy at the expense of manganese. When oxygen, either in the form of air or as oxides, has been tried for decarburising, manganese has been invariably oxidised, and, although carbon has been to some extent removed, this loss is out of the proportion to the manganese lost.

In conclusion, it must be pointed out that the metal can only be produced from its ore by means of a reagent having a greater affinity for oxygen than manganese has, or for which manganese has a greater affinity than oxygen. Only aluminium and carbon have been proved available for this purpose; the former is inadmissible on economical grounds, and the latter produces a carbide and not the metal. This carbide cannot be decomposed, or, in other words, the metal rendered carbon-free, by any practical method except with the expenditure of a large percentage of manganese or by the introduction of an

undesirable element. Even under these circumstances the removal of carbon is only partial.

The author again wishes to thank Professor Gowland, F.R.S., and Mr. Merrett, A.R.S.M., F.I.C., for the many facilities they have placed at his disposal, and for the use of the metallurgical laboratories of the Royal School of Mines, in which this research was carried out.

#### IV.

## CONTRIBUTION TO THE STUDY OF STEEL FOR GEARS.

BY LOUIS P. M. RÉVILLON (PARIS).

### INTRODUCTION.

THE object of these investigations has been to institute as stringent a comparison as possible between the properties and the applications of steels actually recommended by metallurgical establishments for the manufacture of machine parts of great strength, and in particular of those which are employed by the leading builders of motor cars for the making of speed change gears, pinions, and differential crown wheels.

In the difficulty which surrounds one in the presence of widely differing qualities of metal recommended as suitable for the manufacture of a given part, it is impossible to ascertain exactly the relative qualities of all these products except by carrying out a systematic series of tests upon all of them, effected under strictly analogous conditions and with scientific accuracy sufficient to confer on the results the intrinsic value sought. Under these conditions the results might serve as the basis for the judicious selection of a metal corresponding in qualities with the conception which might have been formed beforehand as to the ideal metal required for a given purpose.

These researches have been carried out, during one year only, on the leading types of steel offered by French manufacturers for the construction of gears, and upon products supplied from two German steelworks. While they have already furnished some interesting results, they ought not to end at the point they have reached. The conclusions respecting special steels, for instance, cannot certainly be regarded as



final, and if the field of investigation appears to focus itself upon certain types, it may nevertheless be safely believed that advantageous modifications alike in composition, manufacture, and treatment of the best of these steels might be introduced, leading, little by little, to the avoidance of certain defects, such, *e.g.*, as deformation on quenching. Indeed, the author hopes to be able to pursue, at every opportunity, the comparison thus commenced by subjecting to the same tests, and under strictly identical conditions, every metal recommended as suitable for a specific purpose that may come under his notice.

Such an investigation might be usefully applied to other machine parts, and will, the author hopes, be undertaken by him sooner or later, in respect of all the mechanical parts of a motor car.

#### MECHANICAL CONDITIONS UNDER WHICH A GEAR IS EMPLOYED.

The speed change gear of a motor vehicle consists of a series of wheels and toothed pinions keyed on two or more parallel shafts in such a manner that those on the primary shaft are keyed thereto very rigidly, while the others are given some degree of side play on their shafts, so as to be freely thrown in or out of gear. The crown wheel and the pinion, which, by its sliding displacement, engages with the corresponding toothed wheel, should actuate the shaft and so transmit the full power of the motor to the wheels. Several important considerations as to the properties of the materials to be employed arise out of the needs of construction resulting from these conditions, and manufacturers should direct their attention to the selection of a steel for gears possessing the following qualifications:—

(i.) *In the ordinary condition* under which the metal will be prepared and machined, it should lend itself readily to forging, be sound, thoroughly homogeneous, and capable of being punched out into rough shapes approximating closely in size to the finished parts, in order to reduce the weight of metal used for the rough piece, a consideration of some importance

as regards cost of production in the case of relatively expensive alloys, besides which the forged blanks and rollers acquire, as the result of this treatment, excellent qualities of grain and of tensile strength. The steel should likewise permit of easy turning on the lathe.

While the machining of very hard steels can be effected by the use of high speed steel tools, it is difficult, in a machine shop, to deal with a metal with a higher tensile strength than 75 to 80 kilogrammes per square millimetre. Beyond these figures the diminution of the output proceeds apace, without regard to the hardness. It will be seen later that steels possessing a higher tensile strength than 80 kilogrammes per square millimetre are, besides, entirely within the range of those steels which remain martensitic in the annealed state, and become practically impossible to machine. In addition to this these steels are frequently heterogeneous even within the same piece, if it be at all large, and grave difficulties may be encountered in their employment. Of this nature, in particular, are steels containing high percentages of nickel—from 5 to 6 per cent.—and very little carbon, as will be seen later.

(ii.) *As heat treated* the metal should be capable of taking the greatest possible hardness, combined with but very slight brittleness, in order that it may usefully be worked at high pressures with the teeth in contact. Surface hardness is, in this instance, much more to be desired than tensile strength, and entails different effects. It may here be recalled that for special steels, as for quenched steels, the law as to the relation of hardness to tensile strength no longer holds good.

Non-brittleness is of equally great importance, for it must be recognised that the running of a gear is frequently accompanied by shocks when thrown in and out of clutch, which is too often suddenly effected, while during changes in speed these shocks, which occur at the moment of engaging between two wheels, both already in rotation, are violent, and as they affect only small areas of metal at the outer portions of the teeth, they become the more objectionable.

The best steel for the purpose under investigation in this research—the ideal steel for gears—should therefore be a

metal easy to obtain and to replace, and easy to forge. To take a mechanical standard, it is desirable that it should possess, after annealing, the following qualities:—

Tensile strength . . . . .	70 kilogrammes.
Elastic limit . . . . .	48 „
Elongation . . . . .	20 per cent.
Contraction . . . . .	50 „
Resistance to shock . . . . .	15 kilogrammetres.

It should be heat treated, after the machining be completed, by being quenched at a temperature lying within a fairly lengthy range—at least  $100^{\circ}$ —without requiring either wide or ultimate annealing, and it should then possess the following properties:—

Tensile strength . . . . .	170 kilogrammes.
Elastic limit . . . . .	150 „
Elongation . . . . .	7 to 8 per cent.
Contraction . . . . .	30 per cent.
Resistance to shock . . . . .	7 kilogrammetres.

and a hardness number of about 400 and upwards.

Such a steel would, however, be the ideal metal not for gears alone; its applications in machine construction would be innumerable, and its cost of production might be somewhat high, inasmuch as it would certainly supply the place of steels used in present practice, as it would yield, for a smaller weight, the same degrees of security.

Does such a metal as the foregoing exist? This is the question that is to be investigated by comparing together the various steels which the author has been able to meet with. It will also be seen which products amongst those subjected to trial approximate most closely in properties to those enumerated above, and how they should be manipulated to obtain the best results. Also it will be seen what requirements it might even be advisable to sacrifice in exchange for obtaining, amongst those remaining, values surpassing—in some cases largely—those specified above. In the succeeding pages it is to be understood that the shock test numbers refer to tests made by Mesnager's method on notched bars, while the hardness numbers refer to those obtained by Brinell's method.

## PART I.

## THE PRELIMINARY ARRANGEMENTS AND EXPERIMENTS.

(i.) *Selection of the Steel.*—As has already been stated, there were sought for, from French steelworks, the various steels on the market for the manufacture of gears, and from each such works there were ordered a rolled bar 20 millimetres in diameter, which served for the laboratory tests, and two descriptions of forged rollers, which were each worked up into the high speed pinion and crown wheel, for a speed change gear appliance of the ordinary commercial type.

Table I. gives a list of the steels employed.

The analyses were carried out simultaneously on the rolled bars and on drillings from the forged rollers, and the agreement in the results was perfect, such slight differences as were found being imputable as much to experimental error as to a small degree of inherent heterogeneity in the material. The influence of such differences on the results to be drawn from the investigations should, however, be *nil*.

The estimation of the carbon was made by the method and with the apparatus devised by Wiborg. Combustion, in the case of steels as low in chromium as were the samples under investigation, is not difficult, and no errors arise from the presence of the chromium; while, on the other hand, direct solution is very effective in disintegrating very hard steels and in subsequently burning off the carbon completely, even when small quantities of carbide are present.

The nickel, after elimination of the greater portion of the iron by the separation of the chlorides by ether (in accordance with Rothe's process), was deposited by electrolysis from an ammoniacal solution, this method having been found both feasible and accurate even in the presence of a small quantity of chromium, provided the precaution be taken to mask the presence of the latter element by the addition of sulphate of sodium. The results obtained by this mode of operating are perfectly in harmony with those yielded by obtaining a liquid

TABLE I.—*Analysis of Steels Tested.*

Designation.	Reference.	Carbon.	Manganese.	Silicon.	Sulphur.	Phosphorus.	Nickel.	Chromium.	Vanadium.	No of Class.
		Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	
A	213V	0.217	0.54	0.36	0.014	0.009	2.19	0.35	nil	2
B	214V	0.172	0.13	0.084	0.018	traces	15.52	nil	"	4
C	380V	0.392	0.68	0.35	0.021	0.018	5.19	0.78	"	4
D	215V	0.248	0.25	0.084	0.043	0.027	2.75	0.48	"	2
E	216V	0.157	0.48	0.081	0.024	0.005	7.57	traces	"	4
F	220V	0.425	0.27	0.20	0.042	0.006	2.86	1.20	traces	2
G	230V	0.422	0.22	0.11	0.057	0.013	4.09	0.31	nil	2
H	280V	0.101	0.35	0.31	0.035	0.003	5.36	1.75	"	3
I	316	0.152	0.40	0.43	traces	0.040	1.19	nil	"	4
J	287V	0.394	0.52	1.98	0.027	traces	traces	"	"	1
K	288V	0.360	0.37	0.23	0.053	0.006	4.20	1.15	"	4
L	178X	0.173	0.53	0.16	"	"	3.47	0.18	"	2
M	177X	0.253	0.52	0.17	"	"	3.82	1.28	"	3
N	363V	0.306	0.70	0.17	0.021	0.014	2.75	1.48	"	3
O	178V	0.518	0.27	0.39	0.030	0.006	2.80	0.43	"	3
P	46V	0.477	0.95	0.27	0.035	0.013	4.90	traces	"	4
Q	225X	0.105	0.43	0.11	0.030	0.014	4.38	0.85	"	2
R	919X	0.450	0.28	"	"	"	2.25	0.58	"	2
S	920X	0.862	0.23	"	"	"	0.86	0.06	0.07	3
T	921X	0.771	0.32	"	"	"	0.88	0.06	0.06	1
U	922X	0.266	0.39	"	"	"	1.13	0.19	0.03	3
V	340X	0.265	0.24	"	"	"	4.90	0.85	0.06	4
W	805V	0.401	0.57	1.27	"	"	4.40	2.33	nil	4
X	863V	0.571	0.61	1.89	"	"	nil	"	"	1
Y	987X	0.501	0.64	1.64	"	"	"	"	"	1
Z	988X	0.702	0.78	1.87	"	"	"	"	"	1



in which care has been taken to separate, beforehand, all the chromium by oxidising it to the state of chromate, and dissolving it. The latter process is, however, tediously long, as the chromate becomes mechanically entangled with the precipitated particles of nickel oxide, and it is often necessary to carry out ten to twelve oxidations, followed by solution, before the elimination of the chromium becomes complete. In certain cases, particularly when the quantity of chromium present is relatively high, as compared with the percentage of nickel, it is, moreover, absolutely necessary to revert to a mixed process for separation. Thus, after having effected preliminary elimination of the chromium by oxidation, and having thus got rid of the bulk of this metal, recourse may subsequently be had to electrolysis, in the presence, that is, of sodium sulphite, to mask the small proportion of chromium mechanically carried down, and thus a good deposition of the whole of the nickel may be secured. Generally the nickel deposited under such conditions is rather blacker than that obtained in a pure solution, but no appreciable increase in weight was discernible.

Chromium is estimated volumetrically without its being even necessary to effect any separation either of iron or nickel.

In the sulphuric acid solution of the steel the chromium is converted into the peroxide condition by adding a highly concentrated solution of permanganate of potassium, until the coloration remains permanent, and maintaining the solution at boiling point for half-an-hour. To remove the excess of permanganate a few pieces of paper are added, which soon discharge the colour by forming oxide of manganese. The solution is then filtered and a known excess of ferrous sulphate solution added, the quantity of which remaining unoxidised by the chromium is subsequently titrated with permanganate.

(ii.) *Preparation of the Samples.*—From the rolled bar as delivered there were taken pieces from which were cut, in the cold, either in the lathe or on a milling machine, test-pieces for the most varied tests which the appliances in the laboratory admitted of. The tests, from the mechanical point of view, included tensile tests, shock tests, and hardness tests, with, in addition, the determination of the transformation points.



For the tensile tests the prepared bars were of the following dimensions: diameter, 13·8 millimetres; area, 150 square millimetres; length between punch marks at the base of the shoulder connecting the pieces with the heads, 100 millimetres.

The testing machine used during the tests gave a maximum stress equal to 25,000 kilogrammes, mechanically controlled and worked by hydraulic pressure on the Delaloe system. It was furnished with a steam governor, which maintained the exact equilibrium of a steelyard which measured the force applied. The displacement of the weight controlled the vertical movement of the needle of the registering apparatus and recorded itself as a co-ordinate on the diagram, while the elongation arising each second was recorded by the jaws of the clamp holding the test-piece, which actuated, by differential motion, the rotation of a drum, the elongation being recorded as the abscissa of the curve.

To determine the elastic limit the point of break on the diagram at which the progressive elongations ceased was ascertained. The total load at this moment, divided by the original cross sectional area of the test-piece, gives the elastic limit, *E*, per unit of surface.

The maximum load reached during a given test calculated per square millimetre of cross sectional area gives the value of the tensile strength. Elongation was measured after fracture by determining the distance between the punch marks originally made 100 millimetres apart. After having conveniently readjusted the two portions of the test-piece, the measured length, *minus* 100, yielded the elongation value without further calculation.

Finally, this test affords a measurement of the contraction by dividing the reduced area of cross section obtained during testing by the initial area of cross section; the smallest diameter is measured after fracture, and the contraction ascertained by the formula:

$$\text{Contraction} = \frac{S - S'}{S} \times 100.$$

In several instances the pieces failed to fracture under the maximum stress developed by this testing machine, *i.e.* 25,000

kilogrammes. This was equal to a strength per square millimetre of 170,000 kilogrammes. In such cases, in order to ascertain the exact figure, the total diameter of the test-piece was reduced by means of the machine used to straighten the quenched pieces, and the metal submitted afresh to a test, but fresh punch marks were made at such a distance apart that the ratio between the length and the cross sectional area should conform to the formula of the International Commission:—

$$L = \sqrt{66 \cdot 67 S}.$$

The elongation ascertained in this test is reduced to 100 millimetres to give the true elongation value. In addition to this, in two cases, at the time of the first testing, the bar had already attained a certain degree of permanent elongation, the elastic limit having been reached or exceeded. This amount of elongation was added to that ascertained at the second testing, to rectify the true percentage elongation of the metal. The tensile tests, as indeed all the mechanical tests, have been carried out on the metal subjected to different reheatings in such a manner as to ascertain which might be the most appropriate thermal treatment, capable of conferring the maximum softness on the metal without impairing in any way its qualities. The steel should thus possess the maximum elongation and reduction of area, simultaneously with the minimum tensile strength and elastic limit. Several trials were found necessary accurately to determine the necessary temperature. Generally speaking, the differences in the treatment may be fairly wide so far as the temperature to be attained is concerned, the latter not being here defined nearer than within about 25° up or down. The most important point to consider is the accurate conduct of the cooling process which follows the heating. It should be as gradual as possible, particularly at the moment of passing the transformation points.

Even for accurate experiments it is possible to employ works furnaces on condition that their temperatures are ascertained with strict care, and that the pieces to be reheated are placed in large boxes packed with drillings from good pig iron, well shaken down to insure that the cooling shall be very slow.

The following details show the mode of operation followed in all the reheating experiments made in connection with this research.

The test-piece under investigation was placed, according to its shape, in the centre of an iron or cast-steel box of at least 120 millimetres in diameter, and sometimes larger, so as to secure a clear space of at least 50 millimetres in length on all sides between the test-piece and the sides of the box. In this space were packed drillings of fine-grained pig iron and thin turnings. Experience has shown that there is no trace either of oxidation or of carburisation even after twenty-four hours' heating if the packing has already been used at least once before to burn off the oil which it may be associated with from the workshop. It is the pig iron only which absorbs the oxygen from the faint traces of entangled air. Such a reheating may be carried as high as  $1000^{\circ}$  without danger, but above this temperature it was sometimes found that the pig iron commenced to soften at some superheated point, and to fuse on to the test-piece, occasioning some local carburisation of the latter. The box, tightly closed by a cover luted on with a little fireclay, is introduced into the furnace when the latter is at a temperature in the neighbourhood of that to be attained, and is left there for a predetermined period, found by preliminary experiment, and sufficient to permit of the heat soaking thoroughly to the centre. This period varies with the diameter of the box, and an additional half hour may be added for the actual reheating itself. During this period the temperature of the walls of the box are from time to time determined by means of the Féry optical pyrometer and of a carefully standardised galvanometer, the heating being regulated by adjusting the air and gas inlet valves to secure the temperature desired for the experiment. After the heating has been continued for the requisite time, as above, the box can be removed from the furnace and simply placed in a position sheltered from air currents. The cooling proceeds very slowly, and after twelve hours the temperature still remains at  $70^{\circ}$ , but at this temperature the box may be opened without any apprehension of causing a chilling effect on the test-piece.

Shock tests were carried out on all the samples concurrently with the tensile tests. Two pieces of 60 millimetres in length were planed to a square section, about 10 by 10 millimetres in area, and carefully adjusted to this size by filing. In the middle of one of the sides a notch, 2 millimetres wide and 2 millimetres deep, was made by means of a chisel, the bottom being rounded to a radius of 1 millimetre. The test-pieces were of the type described by Mesnager, and all the tests of this description were made in duplicate for the different thermal treatments of each metal. Over two hundred pieces were broken. The testing apparatus employed was the rotary falling weight machine of Guillery, the available energy of which is 60 kilogrammetres. The results given by this appliance are very satisfactory, and quite comparable with one another, except for steels having a resistance lower than 2 kilogrammetres, in which small experimental errors assume too great an importance. As a matter of fact, however, it is illusory to seek to compare steels yielding such low results, or to classify them, as they are all very brittle, and should be considered as too much so to subserve any mechanical requirements.

The opportunity presented itself of making one of the steels under investigation the subject of a series of shock tests at variable temperatures. The results, however, relate to another research undertaken conjointly with Mr. Guillet, of which the preliminary results have already appeared elsewhere,\* and they are but referred to here in passing, the curious results obtained being briefly noted in connection with other results obtained with the same metal, when that portion of the Report in which the latter is dealt with is reached.

Hardness has, as was seen above, an important bearing on the question of the mechanical strength of gears. To determine this property the laboratory had at its disposal only an old apparatus for the Brinell ball hardness test method. Despite all that has been done to study the physical phenomena which accompany the indentations by the ball at constant pressure, it would appear impossible to take into

\* *Revue de Métallurgie*, 1909, No. 1.

account all the causes of error, except by the method described by Martens and Heyn.\*

Constant pressure machines cannot lay claim to the same accuracy, nevertheless the classification of the metals always ranges itself in the same sequence, and if it is not possible to compare the figures obtained in order to establish a ratio between the degrees of hardness, the conclusions which may be drawn are nevertheless not wholly erroneous as regards the detection of the increase or diminution of the hardness.

All the tests were carried out with an apparatus permitting of a regulated pressure, which was always maintained at about 3000 kilogrammes. The ball had a diameter of 10 millimetres, and was of extra hard steel. The surface subjected to experiment was carefully prepared prior to the thermal treatment, and subsequently only lightly touched up with fine emery paper in order to remove oxidation and restore a polished surface favourable to the ultimate measurements of the diameter of the depression. The latter was effected with a degree of accuracy within  $\frac{1}{1000}$  of a millimetre by means of a displacement microscope and micrometer screw. It is to be understood that to obtain the exact number the operation was conducted by measurements taken in two perpendicular directions, and that the means obtained served to establish the hardness number, the quotient of the charge per area of the spherical concavity of the depression. In cases where the differences in the measurements were too considerable (over 5 per cent.), the experiment was repeated in the vicinity of the first attempt by means of a fresh ball impression.

(iii.) *Determination of the Transformation Points.*—The determination of the points of transformation on heating and on cooling is, from the theoretical point of view at least, of the greatest importance in furnishing a means for determining, *a priori*, the most suitable temperature of quenching and of reducing the too wide field of experiment.

The apparatus employed was the Le Chatelier double galvanometer, arranged according to the mode introduced by Mr. Saladin, which allows of a curve, which is a function of the

\* *Zeitschrift des Vereins deutschen Ingenieure*, 1908, pp. 1719-1723, translated by the present author in the *Revue de Métallurgie*, 1909, pp. 105-115.



temperatures recorded, being obtained on a photographic plate. It would be superfluous to describe the arrangement here, although it may be well to note a few matters of detail which contributed largely to rendering the observations accurate and to obtaining well-marked curves, on which every variation of direction that can be seen possesses its own precise significance. These precautions consisted of heating the sample in an electric furnace, in a Heraeus tube; of protecting it from all oxidising influences during the heating; and of regulating the temperature by a very gradually stepped rheostat, which can readily be obtained by using a liquid bath.

Two metallic plates, forming the two poles of the resistance, are plunged into a receiver, from which flows a thin stream of water of constant volume. In one and a half hours the amperage rises from 0 to 10, which is the maximum load of the furnace. An automatic syphon arrangement permits of the receiver being emptied when the water has reached to a certain height, and the temperature can be regulated by increasing or decreasing the distance between the plates, which reacts on the maximum amperage, and by regulating the flow of water which reacts on the rate of increase in the intensity of the current, and therefore on the temperature. (See Fig. 1.)

The results record themselves on a photographic plate, giving, as abscissæ, the temperature, and as ordinates, the momentary differences of temperature between the steel sample and the piece of nickel. In order to read the indications it is necessary to standardise the scale of the abscissæ by comparing it with fixed points obtained by the solidification of pure metals, such as gold, silver, and antimony, and the boiling points of certain substances, such as water, naphthaline, and sulphur.

With regard to the conclusions to be drawn from the investigation of the transformation points of the metals subjected to experiment, it will be seen that for those quenching in water the transformation point on cooling is found to occur at a low temperature, and one appreciably removed from the transformation point on heating. In some of the steels examined, as will be seen later, this difference exceeds  $400^{\circ}$ .



According to the results of the tests, the most favourable annealing for these steels is that carried out at a temperature in the neighbourhood of the cooling transformation point, and not in the neighbourhood of the transformation point on heating.

Later on there will be propounded a very plausible hypothesis, to the effect that the period of reheating should

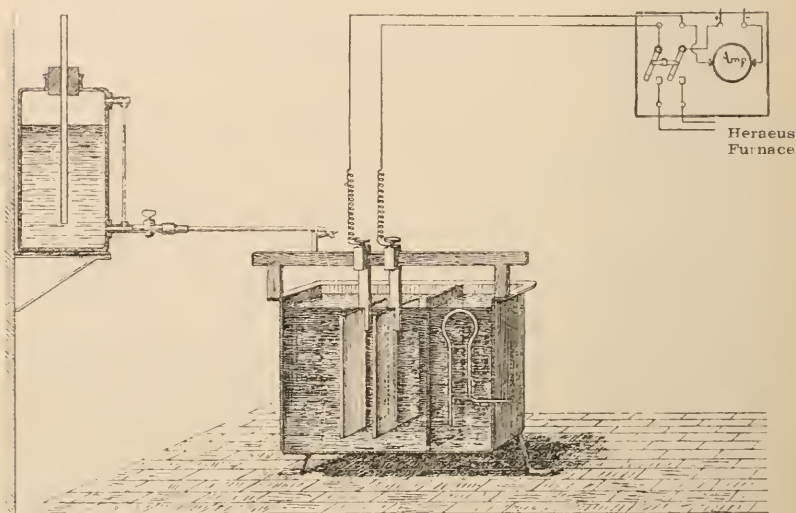


FIG. 1.—Variable Liquid Rheostat for the Heating of a Heraeus Furnace.

undoubtedly be longer in proportion as the difference between the points of cooling and heating transformation are greater.

There are amongst these phenomena certain obscure points which lack of time has prevented the complete elucidation of, but respecting which it would be of great interest to pursue further researches in the future.

It is therefore by taking as a basis the results furnished by the present determinations that it has been possible to select with some accuracy the quenching temperatures, while the nature of the bath has been particularly indicated by the necessity of securing for the steel a high degree of resistance to shock without subsequent reheating. The use of water

does not allow of good results being obtained, except with steels somewhat low in carbon, whereas oil quenching is a paramount necessity whenever the amount of carbon present reaches or exceeds 0.3 per cent. In some instances the results of the tests themselves led to the substitution of oil quenching for water quenching even in the case of steels containing less carbon. In such instances the quality of the steel, due to its method of manufacture and its degree of purity, possesses enormous influence, and it is by no means certain that the divergences found amongst metals of kindred composition might not have been due to these causes.

The researches on quenching temperatures were carried out on the test-pieces alone, and it was the conditions found in these circumstances to be most favourable that were subsequently applied to the corresponding steels after they had been made up into machine parts.

(iv.) *Practical Tests.*—The practical tests were carried out on two cogged crown wheels engaging with each other on the same speed change gear for the highest speeds.

The works which supplied the different bars required for the experiments delivered at the same time and from the same steels four rollers, rolled and forged into two types of form. As has been previously stated, the verification of the correspondence between the composition of the bars and of the rollers was established by analysis made on drillings taken from each piece. The agreement was very close, and thus proved that the metal was, in both cases, derived from the same charge, as had been stipulated.

The untreated rollers were turned up and finished into two crown wheels of twenty-one teeth (Fig. 2) and two pinions of nineteen teeth (Fig. 3), in accordance with the usual form of three-speed gears for a 12 horse-power apparatus of brake-horse-power type (1908 model). The crown wheel was then mounted on the sliding piece of the secondary axle of the speed change, and the pinion keyed direct on the primary axle driven by the motor. The other parts completing the appliance were of the type usually employed in workshops for such purposes.

For each steel a pair of these parts was treated by quenching in such a manner as to confer upon it the typically best

properties corresponding with the theoretical tests, and they were subsequently mounted in the apparatus for trial.

The arrangement for effecting the tests consisted originally of a 4-cylinder motor of 15 nominal horse-power, placed at the author's disposal for the purpose of these trials. It was

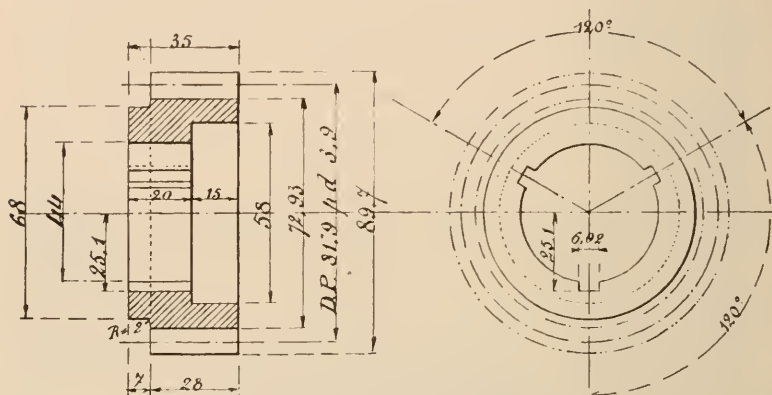


FIG. 2.—High-speed Crown Wheel (21 teeth).

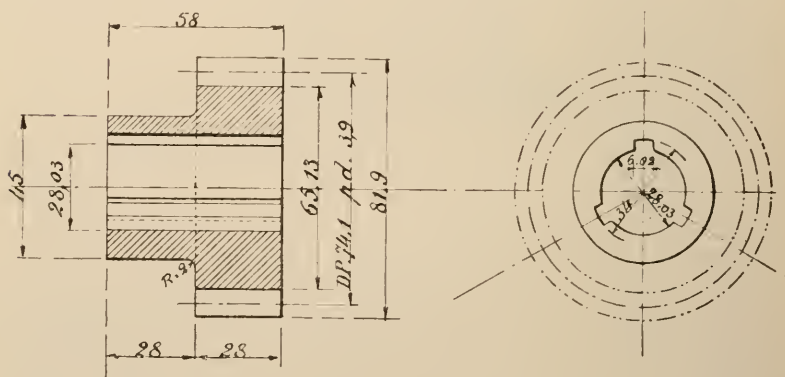


FIG. 3.—High-speed Pinion (19 teeth).

run in this form during several months, actuating by clutch transmission the primary axle of the change speed gear, with a fly-wheel interposed. But subsequently, and for the final trials, this motor had to be replaced by an electric motor of similar power, placed in circuit with the general power supply of the works.

In both instances, in order to absorb the available power and to supply the brake power necessary to the proper working of the gear, the secondary axle was coupled up by a clutch to a continuous current dynamo, which delivered its current to the works main at 110 volts, through a commutator switch, which prevented a reversal of the current in the event of the

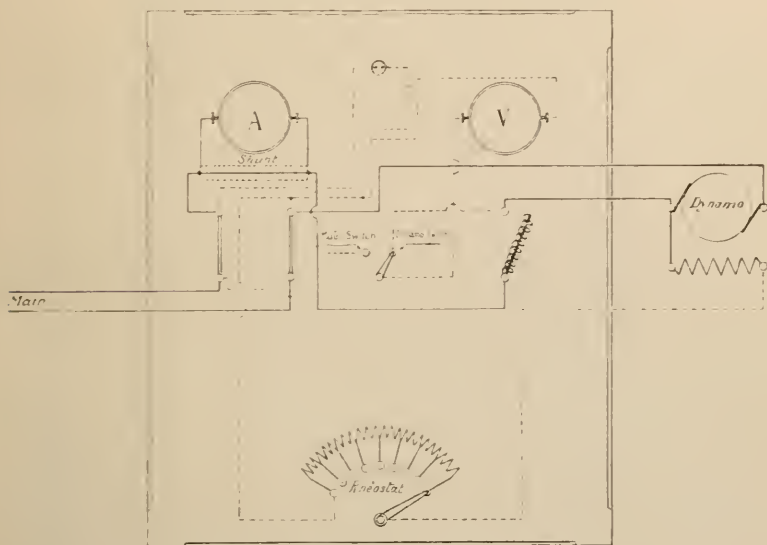


FIG. 4.—Diagram of the Connections.

speed on the test-bed falling, and thus diminishing the voltage below that of the general distribution system.

The electrical combination employed, which was fairly simple, is shown in Fig. 4.

During the running of the explosion motor the substitution of the different gears for one another was regulated by the consumption of the spirit. The motor was run at full capacity until it had consumed 250 litres of spirit, and during the last hour some gearing trials were made, in addition, at the second and third speeds, running at diminished velocities in such a way as to provoke those concussions between the

teeth which frequently accompany speed changes carelessly carried out and accompanied by imperfect unlocking. Although there were carried out but five of the latter operations in each series, there was found, in several instances, a fairly marked amount of wear, which indicated clearly enough the in-

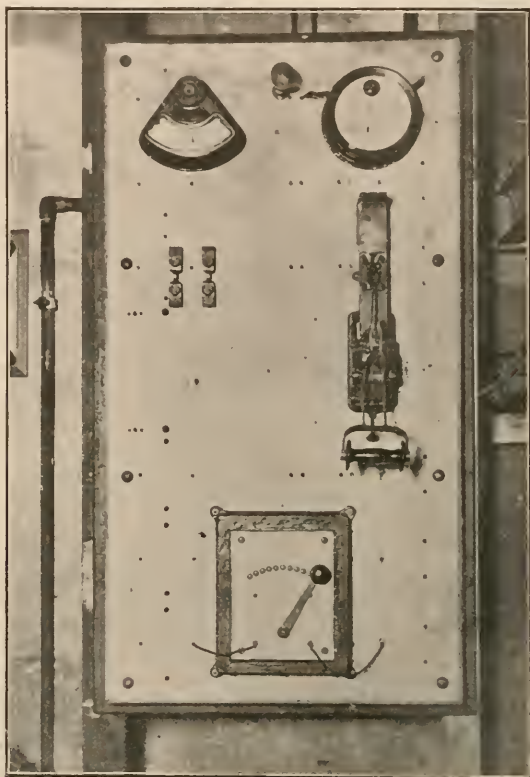


FIG. 5.—Switch Board and Connections.

feriority of the material. When the gears were driven off the electric motor, the latter was allowed to run ten hours per diem for eight consecutive days, in order to realise, as far as possible, uniform conditions as to duration of trial and total power transmitted. The locking and unlocking were carried out by letting the apparatus run free. For this purpose the



current from the generator was partly cut off, and the electric motor slowed down a little. By this means the conditions under which shocks occur in practice, on changing speed, were more or less closely reproduced.

It is quite plain that such a trial is too brief to enable one to judge fairly as to a steel, but it may be pointed out that, even under such conditions, not all the steels yielded absolutely

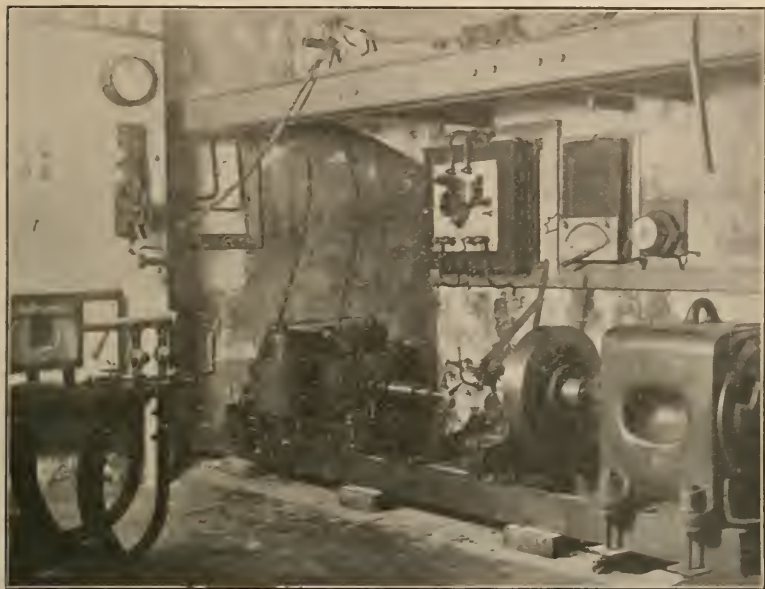


FIG. 6.—Disposition of the Appliances for the Testing of the Gears.

unimpeachable results, and it became possible to reject them once and for all, as in practice it is not a question of requiring eight days' work from the part, but that of several years, and frequently much difficult redressing is required before their renewal is even contemplated.

It would be an advantage to rig up a few apparatus on carriages in regular service, making use of the best of the steels as found by this preliminary selection, and to ascertain what length of time occurs before the pinions and crown wheels are



put out of service. Besides the time requisite for such experiments, the comparison would, however, become very difficult, because the different carriages would not be working under identical conditions, and no means would exist of in any way checking the data that might be furnished by the proprietors or drivers of such automobiles.

The steels which have yielded good results in this preliminary trial will be again experimented upon for a longer period, under the same conditions, for thirty days each, but it will not be possible for some little time hence to decide definitely, from the results of this fresh comparison, as to their relative values.

Amongst all these steels, and in order to facilitate the presentation and comparison of the results, four classes were distinguished, their distinctive features being based on the following differences:—

*Class I.*—This comprised the steels which contained neither nickel nor chromium. They were, generally speaking, manganese-silicon steels, to which had been added certain similar metals. They are distinguished in Table I. by the letters I, J, S, W, X, Y, and Z.

*Class II.*—Nickel-chromium steels with low percentages of nickel and low and medium percentages of carbon, quenching in water or oil. They are indicated by the letters A, D, F, L, and Q.

*Class III.*—Nickel-chromium steels with low percentages of nickel and higher percentages of carbon, quenching in oil and sometimes even in air. They are shown in Table I. by the letters G, M, N, O, R, T.

*Class IV.*—This comprised steels with a medium percentage of nickel, either with or without chromium, and a variable percentage of carbon. They were frequently capable of undergoing air quenching, and are distinguished by the letters B, C, E, H, K, P, U, and V.

The steels comprised within any one of these classes are not, however, entirely comparable with one another owing to differences in their method of manufacture. Some of them were made by the open-hearth process, in large quantities, others were made in crucibles alone, while, finally, the electric

furnace being now not infrequently in use for obtaining high-class steels, several of the samples employed in the experiments came from firms which employ this method of manufacture.

## PART II.

### EXAMINATION OF THE RESULTS.

*Class I.—Steels containing neither Nickel nor Chromium.*—The properties of the manganese-silicon steels will serve as the starting points of this investigation, as they were employed in the manner usual in workshops when it is sought to improve on the materials supplied, and to select the hardest and least brittle steels.

The results yielded by this metal were, for a considerable period, regarded as excellent, until the time when certain difficulties were encountered in connection with its prolonged use. A few pieces, too soft for their work, wore away prematurely, while, but too often in the course of wear, others revealed cracks resulting from slight shocks. A very small degree of heterogeneity was sufficient to destroy the qualities of the metal.

The standard type of these steels is the metal manufactured for a number of years past and sold commercially under the name of "silicon steel." It is better known in connection with motor-car construction as manganese-silicon steel. The type which may serve as a standard might be defined as one possessing the following composition:—

	Composition per Cent.
Carbon . . . . .	0·55
Silicon . . . . .	1·50
Manganese . . . . .	0·60

Properly annealed it is capable of giving at the same time the following mechanical results:—

Tensile strength . . . . .	78 kilogrammes.
Elastic limit . . . . .	50 „
Elongation . . . . .	19 per cent.
Reduction of area . . . . .	42 „

if it has been carefully manufactured by the open-hearth

process and does not contain, as frequently happens, slag inclusions. Its greatest defect is its brittleness. When it is worked up into forged parts, or even in rolled billets, it possesses hardly any resistance to shock, and despite its 19 per cent. elongation it gives, as shock resistance, only 5 kilogrammetres.\*

Its hardness number may be noted, in passing, as, in numerous instances, tensile tests are not possible on gears, and the tensile strength may conveniently be checked by the Brinell test after annealing. It may be taken as 220.

These tests, which serve well enough to define the metal as received, have no bearing on the ultimate result, as a steel of this description is only employed after quenching and tempering. Here, however, the first difficulty presents itself—how should such a metal be treated? Quenching alone confers on this steel a condition of extreme brittleness, whether carried out in oil or in water. It no longer offers the least resistance to shock, and it absolutely requires to be tempered by reheating. Now this matter of reheating is a most difficult operation to define scientifically, as will be seen later when errors in treatment are dealt with.

Numerous experiments have, however, been carried out with the object of obtaining satisfactory all round properties, and they demonstrate that it is possible, by proper manipulation, to obtain a metal possessing 140 to 150 kilogrammes of tensile strength per square millimetre, and a degree of resistance to shock equal, if not slightly superior to that possessed by the metal in the annealed state. The treatment consists of carrying the tempering of such a steel as that described above to a temperature of  $500^{\circ}$ , after quenching, from  $825^{\circ}$  in water or in oil.

In Table II. will be found, amongst the other results obtained, those which appear to be such as to favour the employment of the steel for making gears. In addition to this application, there may be obtained from such a metal steels fulfilling most of the necessary requirements for use, structurally, in a number of circumstances, but in every instance one is at the mercy of numerous factors, the variations

\* The conditions of this test have already been fully described.

of which entail at times serious trouble, owing to the marked differences which exist between the qualities of the metal as quenched, and those it possesses in the tempered condition.

TABLE II.—*Steels of the First Class.*

Steels . . . . .	I.	J.	S.	W.	X.	Y.	Z.
Temperature of annealing . . . . .	900°	800°	750°	900°	900°	900°	900°
<i>Mechanical Tests.</i>							
Tensile strength . . . . .	61·7	76·8	97	74·4	89·9	86·8	100·2
Elastic limit . . . . .	34·3	55·2	51·3	48·1	52·1	58	56·8
Elongation per cent. . . . .	19·5	20	11	19	15	12·5	15·5
Reduction of area per cent. . . . .	51·2	43·4	23·8	39·8	29·3	20·5	35
Resistance to shock . . . . .	6	6	3	5	3	4·5	3·5
Hardness number . . . . .	197	203	210	207	225	215	241
<i>Transformation Points.</i>							
Cooling . . . . .	765	850°	750°-790°	...	...	...	...
Heating . . . . .	700°	770°	705°	...	...	...	...
Temperature of oil-quenching . . . . .	850°	850°	750°	825°	825°	825°	825°
Temperature of reheating . . . . .	200°	500°	500°	500°	500°	500°	500°
<i>Mechanical Tests.</i>							
Tensile strength . . . . .	196	95	162	125·5	154·3	110	148
Elastic limit . . . . .	191	75·8	156	112	143·8	96·2	139
Elongation per cent. . . . .	3·1	11	1·5	4·5	5·5	4	2·5
Reduction of area per cent. . . . .	13·9	43·4	4·3	12·3	15·3	19·3	16·6
Resistance to shock . . . . .	5·5	6·5	5	5·5	3·5	10·5	6·5
Hardness number . . . . .	422	274	388	315	467	302	435

(a) *Errors in Composition.*—If the steel contain less carbon than the analyses on p. 166 indicate, *i.e.* about 0·5 per cent., it will not harden sufficiently by the above correct treatment, and it becomes necessary to investigate afresh all the properties in order to subject it to, at times, considerable modification at the quenching and tempering temperatures, and to obtain once again a product yielding the characteristics sought. This lack of carbon may not be apparent unless established directly by analysis or by microscopic examination, as from the resistance to shock in the annealed state it is not possible, alone, to draw conclusions, this being a function both of the percentage of carbon, of silicon, and of manganese, and being capable of adjustment to the desired figure by an

increase in any one of the others. The following example will show that this is so: if correctly treated a manganese-silicon steel should be got to yield a hardness of 400, yet after applying the same treatment to a steel containing 0·38 per cent. of carbon, with 1·90 per cent. of silicon, the hardness test showed 275 only.

The reverse error in the percentage of carbon was more apparent, as it is revealed, as a rule, by the tensile test on an annealed bar giving a tensile strength exceeding 85 kilogrammes, or an elongation falling below 15 per cent. It should be at least equally feared, since, after the correct treatment, the elongations become very small—1 to 2 per cent.—the steel is very brittle, giving at most 2 kilogrammetres, and it becomes rather difficult to restore the normal characteristics, even by changing the thermal treatment, tempering having already been carried out at 500°.

When, in an analogous steel the error in composition occurs, on the contrary, by a lowering in the percentage of silicon, the metal becomes appreciably more brittle in the annealed state, and particularly in the quenched and tempered state, than the normal manganese-silicon steel, and the product then approximates to hard, open-hearth steel, the employments of which, in machinery, does not always give immense satisfaction. The influence of the proportion of manganese, from 0·3 to 0·8 per cent., is of little consequence; this element increases the strength and the hardness.

(b) *Errors of Treatment.*—A definition of quenching is comparatively easy, and its temperature is very nearly constant for all the steels of this description, small errors, even when amounting to a variation of 775° to 875°, instead of 825°, being practically without influence on the properties of the resulting product. In the same way the results obtained seem to be equally suitable either on water quenching, or on quenching in oil, at the same temperature, followed by the same amount of tempering, when the quality of the metal admits of its being quenched in water without cracking. This is particularly the case when the steel is free from impurities, such as oxides or slag inclusions. The following are some of the results obtained in the two instances:—



*Quenched in Water and Tempered.*

Tensile strength	. . . . .	148·5 kilogrammes.
Elastic limit	. . . . .	137        „
Elongation	. . . . .	5·5 per cent.
Reduction of area	. . . . .	24·35    „
Shock resistance	. . . . .	3 kilogrammetres.

*Quenched and Tempered in Oil.*

Tensile strength	. . . . .	154·3 kilogrammes.
Elastic limit	. . . . .	143·8        „
Elongation	. . . . .	5·5 per cent.
Reduction of area	. . . . .	15·30    „
Shock resistance	. . . . .	3·5 kilogrammetres.

The factor, however, which it becomes practically impossible to determine, for every case, is the condition of tempering. Even when the operation is carried out with a saline bath, the temperature of which has been accurately determined, it is impossible to ascertain how the pieces plunged into the bath will “take” the heat, or with what velocity the thermal exchanges will take place, and consequently, for how long the parts are subjected to the maximum tempering temperature. Sometimes there may be brought to the workshop a piece differing either in shape or in volume from those which have preceded it, and the experiments have to be begun all over again, in order to make certain of reproducing in all circumstances the same tensile strength, and the same degree of hardness. For even stronger reasons, when the tempering is effected simply by leaving the metal for a certain length of time in a furnace heated to a temperature higher than that of tempering, there is no longer any certainty of carrying out the operation with accuracy. Not all the parts of the piece become equally heated on exposure to the same atmosphere, and the ends often exhibit more pronounced softening, and thin portions will at times reach a cherry red heat before the body of the piece itself has been tempered sufficiently to remove the brittleness. In gear wheels the ends of the teeth, which should possess the maximum hardness, are, on the contrary, the surfaces most softened, and it is impossible to know whether the desired temperature has been reached, or whether it has not perhaps been exceeded.



It must, however, be admitted that all steels requiring similarly complex treatment display the same uncertainty in contrast to the uniformity in the results that one is justified in expecting after having taken the precaution scientifically to define the treatment, and that this argument, which constitutes one of the gravest drawbacks to the use of manganese-silicon steels, gains additional strength in numerous instances.

Other metals of somewhat similar nature were therefore sought, the manufacturers being, above all things, desirous of obtaining a material which should not be costly, and yet should yield on simple treatment satisfactory results. One of the works therefore proffered a steel somewhat high in carbon and containing about 1 per cent. of nickel. This metal has been distinguished by the letter I, and its analysis is shown in Table I., but the explanation of its qualities may be sought more in the mode of its manufacture than in its chemical composition alone. It is a steel easy to work, and in the annealed state gives:—

Tensile strength	. . . . .	61.7 kilogrammes.
Elastic limit	. . . . .	34.3 „
Elongation	. . . . .	19.5 per cent.
Reduction of area	. . . . .	51.2 „

The shock resistance is 6 kilogrammes.

This steel requires to be oil quenched at  $850^{\circ}$ , but in this condition it possesses a certain amount of brittleness which has always prevented a good tensile test being carried out. After a very slight tempering at a yellow heat (commencing at about  $200^{\circ}$ ), it was, on the other hand, possible to determine its properties. In these circumstances the steel gave:—

- Tensile strength	. . . . .	196 kilogrammes.
Elastic limit	. . . . .	191 „
Elongation	. . . . .	3.1 per cent.
Reduction of area	. . . . .	13.9 „

and a shock resistance equal to 5.5 kilogrammetres.

In practice it is sometimes possible to avoid this slight tempering, and to use the oil-quenched parts.

Tests on untempered gears gave results that were quite satisfactory. The hardness number, which was originally 420, reached 443 after tempering at  $200^{\circ}$ .

The brittleness increased somewhat, inasmuch as only 4 kilogrammetres were obtained instead of 5·5, and it would be possible to find superior products amongst steels in the other classes. The question of price, which intervenes fundamentally in certain cases, might lead to preference being given to a steel of slightly inferior quality. The one in question presents, indeed, considerable advantages over manganese-silicon steel.

In addition to the foregoing, this steel does not undergo deformation on quenching, provided a few precautions be taken, and it is for this reason that it has already been employed in a number of interesting applications.

*Class II.—Nickel-chromium Steels hardened in Oil or Water.*—Numerous products are included in this category, and the leading steel-making firms have each placed on the market a metal of this nature, the properties of which vary but little with one another. They differ chiefly in their percentages of carbon, and in their general purity, rather than in the proportions of nickel and of chromium, which remain comprised within the following limits: Nickel, 2 to 3 per cent.; chromium, 0·4 to 1 per cent.

The analysis of these products are all given in Table I., the steels composing this class being those designated by the letters A, D, F, L, and Q, while in Table III. will be found their mechanical properties in the annealed state, the condition most suitable for softening the metal preparatory to machining. It will be seen that in this state these steels possess but slight strength, and that they will consequently be very easy to work. For nickel steels they yield on tensile testing rather high elongations, attaining with the softest of them as much as 26 per cent., together with very satisfactory results on shock testing, of which the most remarkable is 18·5 kilogrammetres without breaking. The material in question possesses a tensile strength of 64 kilogrammes per square millimetre of cross section.

Finally, an interesting practical result should be noted. The hardness test by the Brinell method is quite capable of furnishing an indication of the state of the metal and of the character of the annealing it has undergone, and this may be ascertained with sufficient accuracy without the necessity of

impairing the quality of the piece tested. By selecting a suitable place for the test on the annealed and planed roller it is possible to check a large number of pieces prior to final working, and it is easy to remove completely the faint impression of the ball left by this test.

The coefficient  $C$  in the formula  $R = C\Delta$  varies from 0.34 to 0.36, and approaches closely with that used in the case of ordinary soft and half-soft steels.

TABLE III.—*Steels of the Second Class.*

Steels. . . . .	A.	D.	F.	L.	Q.
Chemical composition—					
Carbon . . . . .	0.217	0.248	0.425	0.173	0.105
Manganese . . . . .	0.54	0.25	0.27	0.53	0.34
Nickel . . . . .	2.19	2.75	2.86	3.47	4.38
Chromium . . . . .	0.35	0.48	1.20	0.18	0.85
Transformation points—					
Heating . . . . .	800°	795°	820°	775°–800°	750°–800°
Cooling . . . . .	680°	690°	685°	670°–725°	690°–625°
Annealed—					
Temperature . . . . .	800°	800°	700°	900°	800°
Tensile strength . . . . .	56.1	61.2	74.1	61	63.7
Elastic limit . . . . .	39.6	43	51.8	36	42.3
Elongation . . . . .	26	23	22	21.5	20
Contraction . . . . .	64.9	55.7	63.2	53	60.5
Shock . . . . .	18.5	9	15.5	5	16
Hardness . . . . .	153	170	197	168	179
Quenched—					
Bath and temperature . . . . .	water, 750°	oil, 800°	oil, 800° reheated at 300°	oil, 850°	water, 750°
Tensile strength . . . . .	143.8	158.2	186	139	142
Elastic limit . . . . .	127	133.5	151	122	122
Elongation . . . . .	10	7	6.3	5	10
Contraction . . . . .	44.3	19.3	42.7	15.4	54
Shock . . . . .	9.5	6.5	7.5	8.5	10
Hardness . . . . .	370	418	412	328	295

The temperature of annealing exerts a certain degree of influence, particularly on the elongations and on the resistance to shock. Some experiments in this direction were made, and it may be remarked that much interest attaches to the fact that, in order to improve the softness of the steel, it is necessary to keep very decidedly below the temperature which, in an ordinary steel containing the same percentage of carbon,

confers the best qualities. This phenomenon might, however, have been anticipated beforehand, as the metal appreciably lowers the temperature of the transformation points, and as it is recognised that, at any rate for pearlitic steels, the most favourable annealing should be carried out at a temperature but slightly higher ( $50^{\circ}$  as a maximum).

The following are the results obtained with a dead soft steel:—

*Annealed at  $900^{\circ}$ .*

Tensile strength . . . . .	64.6 kilogrammes.
Elastic limit . . . . .	47.5 „
Elongation . . . . .	19.0 per cent.
Reduction of area . . . . .	61.6 „
Shock resistance . . . . .	8.0 kilogrammetres.
Hardness number . . . . .	184.

*Annealed at  $800^{\circ}$ .*

Tensile strength . . . . .	63.7 kilogrammes.
Elastic limit . . . . .	42.3 „
Elongation . . . . .	20.0 per cent.
Reduction of area . . . . .	60.5 „
Shock resistance . . . . .	16.0 kilogrammetres.
Hardness number . . . . .	179.

For steel F, which is already harder owing to its percentage of carbon being higher, the most softening temperature of annealing is situated a little below the transformation point, at  $850^{\circ}$ . Under these circumstances it still yields:—

Tensile strength . . . . .	86.6 kilogrammes.
Elastic limit . . . . .	54.7 „
Elongation . . . . .	16.5 per cent.
Reduction of area . . . . .	61.0 „
Shock resistance . . . . .	8.0 kilogrammetres.
Hardness number . . . . .	221.

whereas at  $700^{\circ}$  the figures do not exceed the following:—

Tensile strength . . . . .	74.5 kilogrammes.
Elastic limit . . . . .	51.8 „
Elongation . . . . .	22.0 per cent.
Reduction of area . . . . .	63.2 „
Shock resistance . . . . .	15.5 kilogrammetres.
Hardness number . . . . .	197.

These conditions on simple inspection appear much more favourable to easy machining than those preceding. From the

micrographic point of view, the steel annealed at  $700^{\circ}$  shows somewhat diffused pearlite in process of transformation, in which it is no longer possible to recognise the exact percentage of carbon, whereas the sample, under the condition of annealing at  $850^{\circ}$ , has already assumed a somewhat martensitic aspect.

(a) *Treated Steels*.—The temperature of quenching was determined from the position of the transformation point of the steel on heating, but the nature of the bath was left to individual predilection.

For all dead soft steels, that is to say, low in carbon, quenching in water was tried first, and gave good results in so far that the metal continued to give good elongations and presented the maximum possible hardness and a fair resistance to shock. For the steels more highly carburised, D, F, and L, on the contrary, the test-piece gave, after quenching in water, an abnormal fracture, and it became necessary to substitute for the water-bath an oil-bath, giving a milder temper and, with steels D and L, satisfactory results.

Lastly, in regard to steel F, it was necessary to have recourse to ultimate reheating, as, after quenching in oil at different temperatures, it was impossible to obtain anything but a test-piece breaking abnormally and possessing an exaggerated degree of brittleness. The study of such a metal becomes very complex, owing to the number of experiments which require to be made before any certainty can be felt of having reached the best result.

Table III. shows the characteristics of steels of the second class under the best conditions of thermal treatment.

Dead soft steels, owing to their low percentage of carbon, can therefore withstand quenching in water. This treatment may, however, confer upon them a condition in which they possess properties comparable with, if not superior to, those of steels low in carbon which have had to be quenched in oil. It does not do, however, for the carbon to be below a certain percentage, in the case of steels containing this proportion of 2 per cent. of nickel, as has occurred in regard to steel Q. In this instance it must be admitted that the amount, 0.105 per cent., must be regarded as too low and the result reacts on

the hardness, as, notwithstanding that the steel possesses a tensile strength of 142 kilogrammes per square millimetre, it was impossible, with the ball test, to obtain a higher hardness number than 295 instead of 370, which was given by steel A. with a tensile strength of 143.

Now, mineralogical hardness possesses industrially a degree of importance which it is necessary strongly to emphasise. Steel Q is in an unsuitable condition, and the firm supplying it has taken this into account, inasmuch as it is sold as a steel for case-hardening. Case-hardening will be dealt

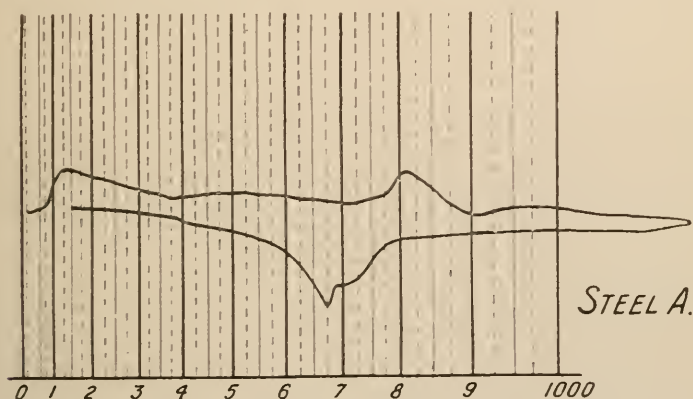


FIG. 7.--Curve for the Determination of the Transformation Points.

with generally at a later stage, when this point will be reverted to.

Steel A should be considered as a superior product; its improvement on quenching is quite remarkable, as the tensile strength rises from 56.1 to 143.8 kilogrammes, while the hardness, which is very low for machining, 153, reaches the limit originally assigned, namely, 400, after quenching (Fig. 7).

Steel L is somewhat beyond the range, as it contains not only 2 per cent., but 3.47 of nickel, which may justify the oil-quenching which has been found necessary.

The shock resistance of steel D is certainly rather low, but the material even as annealed yields but 9 kilogrammetres, for which the percentage of phosphorus in this steel must be



blamed, as it is the highest met with in the special steels analysed for the purposes of this investigation. The amount of phosphorus found in this steel was 0·027 per cent., whereas the others contained only 0·003 to 0·013 per cent.

Other heat treatments were applied to these steels in a similar manner, and have revealed the following facts:—

A slight variation in the quenching temperature is almost without effect on steel A. Thus at 800° the results were:—

Tensile strength . . . . .	142·8 kilogrammes.
Elastic limit . . . . .	123·5 „
Elongation . . . . .	9·0 per cent.
Reduction of area . . . . .	44·5 „
Shock resistance . . . . .	8·5 kilogrammetres.
Hardness number . . . . .	$\Delta=375$ .

There was no reason for pursuing other experiments for this steel, the treatment of which was exceedingly simple, besides which micrography serves to elucidate other circumstances. Whereas, on annealing, steel A presents the microscopic appearance of a low carbon steel containing a certain proportion of nickel, and yielding a serpentine pearlite the appearance of which has been reproduced again and again, after quenching in water an exceedingly finely grained martensitic structure is obtained, the etching of which is very difficult, as it colours but slightly on attack by picric acid. In these circumstances the treatment undergone by steel A seems decidedly the most suitable, and it may be concluded that the steel has been made to yield the best results it is capable of.

Before oil-quenching steel D the treatment recommended by the firm supplying it was tried, namely, quenching in water at 850°, followed by annealing at 500°, which conferred a tensile strength of 99·6 kilogrammes, with 98·5 kilogrammes elastic limit, 12 per cent. elongation, 57·4 per cent. reduction of area, and 8·5 kilogrammetres shock resistance. Additional annealing carried out at lower temperatures did not appreciably improve the tensile strength, while the elongation and the results of the shock test underwent steady diminution. In other respects this treatment obviates none of the uncertainties already noted in connection with annealing.

A test after quenching in water at a lower temperature—

750°—gave a test-piece which broke at the shoulder by torsional strain, and gave only 2·5 kilogrammetres on shock test, and a hardness number of 460, whereas, from the first, oil quenching from a temperature in the near neighbourhood of that of the transformation point gave a highly satisfactory result, which was not reproduced at any other temperature, *e.g.* 850° C.

In the study of steel Q it was sought widely to extend the investigations, notwithstanding that the first experiment at once yielded the best results. The following comparison shows the results of quenching in water from varying temperatures:—

Temperature of Quenching.	Tensile Strength.	Elastic Limit.	Elongation.	Reduction of Area.
Degrees.	Kilogrammes.	Kilogrammes.	Per Cent.	Per Cent.
850	136·5	112·0	10·5	56·0
800	137·0	115·5	10·0	55·1
750	142·0	122·0	10·0	54·0
700	136·2	123·7	10·0	55·5
While oil quenching gave:—				
850	133·0	123·8	10·0	56·0

It will be noticed how little effect the differences in thermal treatment has on the mechanical properties of these steels. Indeed, with such materials the martensitic transformation always occurs with the greatest ease once the region of the transformation points has been exceeded by heating, and in order, on the other hand, to obtain, by cooling, the reverse phenomenon, *i.e.*, a return to a well-defined pearlitic structure, a number of favourable conditions must simultaneously be brought to bear during cooling.

All the quenching tests lead, therefore, to the maintenance of the stable form on heating, as cooling is never sufficiently slow, and in all cases there will be obtained the same quality of product. In the tests described above will be seen the regularity of the elongations, and reductions of area, which is even greater than that of the tensile strength and elastic limit.

If the temperature were raised an unnatural condition of the grain—a kind of crystallisation—would ultimately be produced, and it would only be possible to reduce the elongation without increasing the tensile strength. Besides this, in the conditions in which the experiments were made, micrography furnishes results which help to corroborate the results of the other tests. All the quenchings carried out in these circumstances yielded a perfectly pure martensite of very fine structure, and one that could only with difficulty be coloured, thus showing the sample to have been properly quenched.

The steel Q was similarly made the subject of a series of experiments of a different nature which are not described here, as they form part of a different investigation. The influence of the temperature on the brittleness of steels was studied, and while there were obtained, by heating, transformations in structure, the curve of the variation in tensile strength in functions of the temperature faithfully reproduced the appearance of the curves of ordinary steels, showing a slow increase in resistance, with rising temperature, up to a maximum in the neighbourhood of  $180^{\circ}$ , followed by a decrease until a minimum is reached at  $475^{\circ}$ , a temperature at which the tensile strength is less than it is at the ordinary temperature. Above this there is a rapid increase, and once the test-piece is distinctly red-hot it bends without fracture.

*Class III.—Nickel-chromium Steels with higher Carbon percentages, and therefore capable of Air-quenching.*—In the general table given at the commencement of this research, the steels comprised within this category are distinguished by the letters G, M, N, O, R, and T.

*Steel G.*—This steel, characterised by the firm supplying it as a semi-soft steel, can, as a matter of fact, be brought under certain conditions into an annealed state in which it may be readily machined, but, contrary to the view generally held, it is not possible to ascertain the temperature of this annealing by studying the critical points.

The curve on heating shows a peculiar point at  $760^{\circ}$ , and one would therefore be led to the belief that to carry out the annealing it would be necessary to heat the steel above this temperature. All the experiments which have been made in

the neighbourhood of this temperature, with the object of softening the metal, have failed. Despite the precautions taken to secure a very slow rate of cooling, the steel which has been heated to that temperature, which is distinctly above that of the point of transformation on cooling ( $+400^{\circ}$  to  $+425^{\circ}$ ), passes this particular point with a certain degree of velocity. The curve of cooling, as a function of the speed, starts as a horizontal tangent to the maximum temperature that has been reached, and this tangent rises subsequently to meet anew in a horizontal asymptote at the normal temperature. If it be sought to diminish the speed of the passage past the transformation point on cooling, it would be necessary, in works practice, to endeavour to lower the maximum temperature of annealing, after having obtained as complete protection as possible against heat losses. By rising as close as possible to the cooling transformation point there is obtained, under the same conditions, a lower rate of speed, as this temperature is passed during the moment when the cooling curve has an almost horizontal tangent. In such circumstances the annealing becomes satisfactory without the transformation point on heating having been reached. Indeed at times, as will be seen later, the most suitable annealing has been carried out below the temperature of the cooling transformation point, ascertained by a separate experiment. In order to explain this occurrence it must fairly be admitted that, in respect of the conditions of heating, the positions of these transformation temperatures is not absolutely invariable, but are subject, on the contrary, to modifications which vary somewhat widely with the rate of heating.

These considerations, discussed, as they have been, in some detail, are applicable to the bulk of the steels quenching in air. The latter may be determined in advance; they are those for which the difference between the transformation points on heating and on cooling, respectively, are comparatively small. This hysteresis may, with certain steels of this class, reach as high as  $450^{\circ}$ .

With steel G, the investigation of the most suitable annealing temperatures for softening the metal led to the ultimate adoption of  $600^{\circ}$ , when the tensile strength no longer exceeds

81 kilogrammes per square millimetre, whereas at  $650^{\circ}$  experience showed the metal to possess:—

Tensile strength . . . . .	125·1 kilogrammes.
Elastic limit . . . . .	117·0 „
Elongation . . . . .	11·5 per cent.
Reduction of area . . . . .	38·7 „

and at  $750^{\circ}$  the test yielded:—

Tensile strength . . . . .	147·5 kilogrammes.
Elastic limit . . . . .	118·5 „
Elongation . . . . .	17·0 per cent.
Reduction of area . . . . .	22·0 „

The treatment of this steel recommended by the firm supplying it does not allow of the best properties being obtained in the resulting metal, from the point of view, that is, of the special uses, which were the objects of the present investigation.

Quenched in oil at  $850^{\circ}$  and tempered at  $500^{\circ}$ , as was indicated, it yielded only 106 tensile strength, with 96·5 elastic limit, 12 per cent. elongation, and 59 per cent. reduction of area, whereas on simple cooling in air from  $800^{\circ}$  (which is what may conveniently be termed air quenching at  $800^{\circ}$ ), the properties were as follows:—

Tensile strength . . . . .	155·4 kilogrammes.
Elastic limit . . . . .	133·5 „
Elongation . . . . .	8·0 per cent.
Reduction of area . . . . .	41·0 „

Oil quenching, without subsequent tempering, which is likewise very generally applicable to steels which quench in air, does not, in this instance, give good results. This fact must be attributed to the somewhat high percentage of carbon; the presence of the carbon confers great brittleness on a quenched steel, and with equal tensile strengths in two different steels the most brittle will be that containing the most carbon. The oil-quenched test-piece breaks before having developed its full strength, under the influence of the slightest oblique stress, which induces torsional strains in the neighbourhood of the head.

*Steel N.*—This steel furnishes, on the other hand, an interesting example of the application of oil quenching, and under these conditions it yields the most remarkable results of the



series. Its relatively low percentage of carbon is compensated for by a small increase in the percentage of chromium and manganese, elements both of which increase hardness, particularly after quenching. After air quenching from  $800^{\circ}$  there was obtained :—

Tensile strength . . . . .	189.0 kilogrammes.
Elastic limit . . . . .	188.0 „
Elongation . . . . .	5.0 per cent.
Reduction of area . . . . .	41.0 „
Shock test . . . . .	8.0 kilogrammetres.
Hardness number . . . . .	408.

But as the result of oil quenching, which, owing to its composition, could be carried out, it gave :—

Tensile strength . . . . .	205.5 kilogrammes.
Elastic limit . . . . .	203.5 „
Elongation . . . . .	9.5 per cent.
Reduction of area . . . . .	36.3 „
Shock test . . . . .	8.0 kilogrammetres.
Hardness number . . . . .	425.

It is useless to attempt to improve on these results, for the reasons already given. The modifications within this area, where the steel is martensitic, are very small, and cannot be differentiated from experimental errors, and from the slight differences found between one test-piece and another.

The difficulty relates chiefly to the softening of a steel which, by an annealing carefully carried out at  $900^{\circ}$ , still possesses a tensile strength of 158 kilogrammes per square millimetre. It was necessary to proceed by allowing it to cool slowly, in its box, in the furnace itself, starting at  $600^{\circ}$ , under which conditions the following characteristic properties were obtained :—

Tensile strength . . . . .	94.5 kilogrammes.
Elastic limit . . . . .	88.9 „
Elongation . . . . .	14.5 per cent.
Reduction of area . . . . .	50.2 „
Shock test . . . . .	75.0 kilogrammetres.
Hardness number . . . . .	25.

which constitute the condition of maximum softness for this steel (Fig. 8).



*Steel M.*—This steel owes its properties more to its percentage of nickel and chromium than to its percentage of carbon, which does not exceed that of the steels in the preceding class, besides which it is incapable of yielding the very high results which have just been noted above.

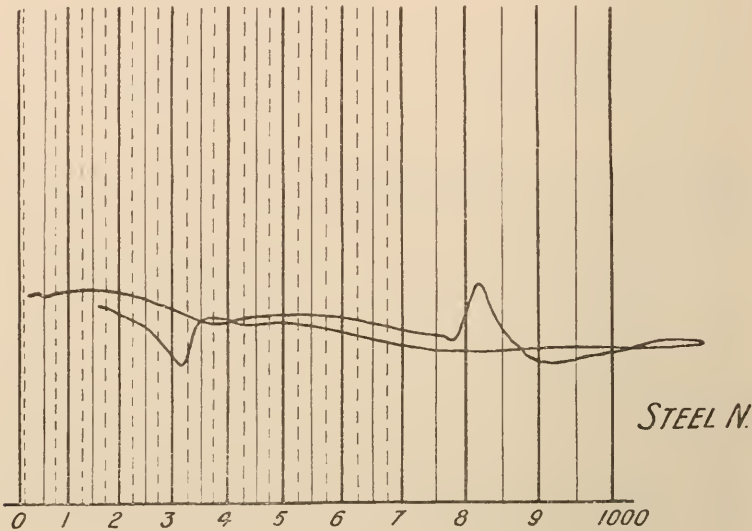


FIG. 8.—Curve for the Determination of the Transformation Points.

The first annealing was carried out at too high a temperature (900°), although even at this temperature it gave a metal capable of being machined, and having :—

Tensile strength . . . . .	97·0 kilograms.
Elastic limit . . . . .	76·8     „
Elongation . . . . .	12·0 per cent.
Reduction of area . . . . .	40·0     „

But on annealing at a more suitable temperature (700°) the metal was appreciably softened, and gave :—

Tensile strength . . . . .	80·6 kilograms.
Elastic limit . . . . .	45·4     „
Elongation . . . . .	17·5 per cent.
Reduction of area . . . . .	50·5     „

By quenching in oil at the most suitable temperature, which

was found to be  $850^{\circ}$ , it does not perhaps harden sufficiently, because of its low percentage of carbon. Its properties then become :—

Tensile strength . . . . .	146.5 kilogrammes.
Elastic limit . . . . .	129.0 „
Elongation . . . . .	9.5 per cent.
Reduction of area . . . . .	51.0 „
Shock resistance . . . . .	6.0 kilogrammetres.
Hardness number . . . . .	313.

It quenches in air as the result of the difference between the transformation points on cooling and heating respectively, but at  $800^{\circ}$  it yields a metal of but little interest, possessing :—

Tensile strength . . . . .	90.4 kilogrammes.
Elastic limit . . . . .	60.1 „
Elongation . . . . .	13.0 per cent.
Reduction of area . . . . .	36.6 „

Finally, it was sought to ascertain how it would behave on quenching in water at a temperature somewhat above  $750^{\circ}$ . The result obtained cannot be compared with the others, as, owing to its too great brittleness, the test-piece broke owing to torsional stress in the head.

*Steel O.*—This steel owes all its hardness to a particularly high percentage of carbon, which does not allow of the expectation of obtaining any considerable softness even by the most carefully carried out reheating. Its machining becomes of considerable difficulty, and if it has had a meed of success in the hands of some builders, its usage could hardly increase in view of the introduction on the market of steels distinctly superior to it. Even its somewhat low price will not assist it to compete.

Annealed at a temperature of  $750^{\circ}$  it was only capable, as a maximum, of manifesting the following properties :—

Tensile strength . . . . .	95.5 kilogrammes.
Elastic limit . . . . .	57.5 „
Elongation . . . . .	14.0 per cent.
Reduction of area . . . . .	49.8 „
Hardness number . . . . .	251.

whereas, treated as an ordinary steel at  $900^{\circ}$ , it gave :—

Tensile strength . . . . .	102.0 kilogrammes.
Elastic limit . . . . .	65.7 „
Elongation . . . . .	12.0 per cent.
Reduction of area . . . . .	50.6 „

The quenching of such a metal can obviously only be carried out in oil or in air. The firm supplying it recommend oil quenching, followed by an annealing only specified in terms of the tempering colour.

All the tests carried out on the steel tempered to a purple ( $250^{\circ}$ ) yielded tensile test-pieces of extreme brittleness, which broke off close to their heads without having developed their full tensile strength, while the test-pieces for the shock test gave the extraordinarily low figure of 2.5 kilogrammetres. By a prolonged tempering at  $300^{\circ}$  for five minutes it was possible to obtain a shock resistance equal to 6 kilogrammetres, while the tensile test-piece gave the following results:—

Tensile strength . . . . .	151.5 kilogrammes.
Elastic limit . . . . .	142.2 „
Elongation . . . . .	7.0 per cent.
Reduction of area . . . . .	42.0 „
Hardness number . . . . .	395.

whereas, if the steel be taken, after quenching, to a temperature of about  $500^{\circ}$ , as is done in annealing manganese-silicon steels, with rapid cooling from this point, the following values are obtained:—

Tensile strength . . . . .	119.0 kilogrammes.
Elastic limit . . . . .	112.0 „
Elongation . . . . .	11.0 per cent.
Reduction of area . . . . .	48.8 „
Shock test . . . . .	6.5 kilogrammetres.
Hardness number . . . . .	342.

results which are altogether insufficient. With this steel there is a reversion, as may be seen, to the multitudinous drawbacks noted in connection with the treatment of manganese-silicon steels, as the result of the lack of precision in regard to the temperatures and lengths of time of reheating for the different portions of the same piece. The very mediocre results obtained afford grounds for the rejection of the metal (Fig. 9).

*Steel R.*—This differs from the preceding sample of steel by a small diminution in the percentage of carbon, but its manufacture is based on the same principles. It certainly furnishes a product more easy to machine, and one that can be more or less softened at variable temperatures when the operation is

carried out under favourable conditions of slow cooling. Thus at  $750^{\circ}$  to  $850^{\circ}$  the following results can be obtained:—

Tensile strength . . . . .	86.5 kilogrammes.
Elastic limit . . . . .	50.2 „
Elongation . . . . .	14.0 per cent.
Reduction of area . . . . .	48.8 „
Shock resistance . . . . .	6.0 kilogrammetres.

When commencing the treatment great difficulties are, however, encountered before obtaining a simple mode of quenching, or a single operation. Quenched in oil the test-piece is

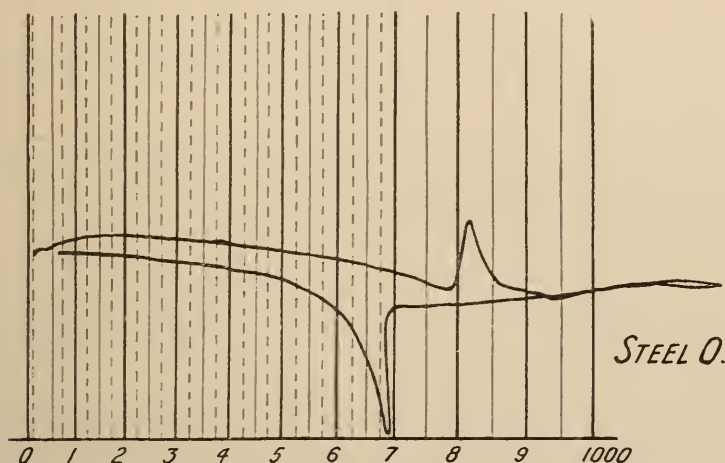


FIG. 9.—Curve for the Determination of the Transformation Points.

too brittle and breaks at the head, without yielding results. Quenched in water and reheated to  $300^{\circ}$ , it is still impossible to obtain a measurable value for the tensile strength, whereas when carried to  $500^{\circ}$  the reheating, after a water quenching at  $800^{\circ}$ , gave a steel possessing the following properties:—

Tensile strength . . . . .	134.0 kilogrammes.
Elastic limit . . . . .	122.0 „
Elongation . . . . .	6.5 per cent.
Reduction of area . . . . .	47.8 „
Shock test . . . . .	11.0 kilogrammetres.
Hardness number . . . . .	301.

which reveals nothing more than may be obtained with a steel

containing less carbon, and therefore less brittle and easier to machine. Finally the air quenching of such a metal is in no way beneficial, inasmuch as the transformation point on cooling is still very high ( $665^{\circ}$ ). It was carried out at  $800^{\circ}$  in order to verify preconceived views, and the results were as follows:—

Tensile strength . . . . .	107·0 kilogrammes.
Elastic limit . . . . .	77·2 „
Elongation . . . . .	10·0 per cent.
Reduction of area . . . . .	21·8 „

*Steel 7.*—The following steel was manufactured as an extreme exemplification of the foregoing theories relative to the proportion of carbon, but the steel is hardly comparable with the others as it only contains, as a special element, 1·13 per cent. of nickel.

The amount of carbon, 0·771 per cent., led, despite all the care taken in an annealing carried out at the temperature of  $750^{\circ}$ , to a test-piece yielding:—

Tensile strength . . . . .	103·0 kilogrammes.
Elastic limit . . . . .	54·4 „
Elongation . . . . .	7·5 per cent.
Reduction of area . . . . .	19·5 „
Shock test . . . . .	3·0 kilogrammetres.

Reheated at temperatures in the same neighbourhood the results were not appreciably different. At  $850^{\circ}$ :—

Tensile strength . . . . .	105·0 kilogrammes.
Elastic limit . . . . .	54·2 „
Elongation . . . . .	8·0 per cent.
Reduction of area . . . . .	15·4 „

At  $700^{\circ}$ :—

Tensile strength . . . . .	108·0 kilogrammes.
Elastic limit . . . . .	61·5 „
Elongation . . . . .	10·0 per cent.
Reduction of area . . . . .	14·0 „

The temperature was, however, lowered to  $600^{\circ}$ , in accordance with the experiments quoted above, that is to say, by more than  $100^{\circ}$  below the transformation point on cooling, which is marked by a distinct break at  $750^{\circ}$ . The result

was a remarkable degree of softening, not to be explained by the theory. The steel in these circumstances yielded:—

Tensile strength . . . . .	84.1 kilogrammes.
Elastic limit . . . . .	59.0 „
Elongation . . . . .	9.5 per cent.
Reduction of area . . . . .	46.7 „
Hardness number . . . . .	273.

The metal is therefore capable of being machined, whereas this was impossible when it possessed a tensile strength of 105 kilogrammes per square millimetre.

Quenching could only be carried out in oil, and even in this case only furnished a test-piece with normal fracture after an annealing carried out at 500°. In these circumstances it gave:—

Tensile strength . . . . .	148.0 kilogrammes.
Elastic limit . . . . .	128.0 „
Elongation . . . . .	6.0 per cent.
Reduction of area . . . . .	14.1 „
Shock test . . . . .	4.6 kilogrammetres.
Hardness number . . . . .	425.

The question was, could this complicated treatment be replaced by air quenching? The experiment was made and the result was as follows:—

Tensile strength . . . . .	110.6 kilogrammes.
Elastic limit . . . . .	67.7 „
Elongation . . . . .	9.5 per cent.
Reduction of area . . . . .	24.4 „

The small amount of difference between the transformation points would readily explain these values.

The best of the results enumerated above have been grouped in Table IV.

The steels of this class, which owe their hardness and their properties of quenching hardness to a somewhat high percentage of carbon are not, generally speaking, very liable to the martensitic transformation, which is so difficult to avoid at the moment of reheating, but they possess at ordinary temperatures, and under the conditions most favourable to their employment, high tensile strength which is directly due to that high percentage of carbon.



They possess excellent qualities of hardness after the proper heat treatment, but this is to the detriment of their resistance to shock, some of them becoming so brittle that it is no

TABLE IV.—*Steels of the Third Class.*

Steels . . . . .	G.	M.	N.	O.	R.	T.
Chemical composition—						
Carbon . . . . .	0·422	0·253	0·306	0·518	0·450	0·771
Manganese . . . . .	0·22	0·52	0·70	0·27	0·34	0·32
Nickel . . . . .	4·09	3·82	2·75	2·80	2·25	1·13
Chromium . . . . .	0·31	1·28	1·48	0·43	0·58	0·19
Transformation points—						
Heating . . . . .	760°	735°–790°	770°–815°	800°	770°	820°
Cooling . . . . .	410°–425°	505°–575°	325	695°	665°	705°
Annealed—						
Temperature . . . . .	600°	900°	600°	750°	750°	600°
Tensile strength . . . . .	81·5	80·6	94·5	95·5	86	84·1
Elastic limit . . . . .	70	45·4	88·9	57·5	50	59
Elongation . . . . .	18	17·5	14·5	14	13	9·5
Contraction . . . . .	65·8	50·5	59·2	49·8	45·5	46·7
Shock . . . . .	14	7·5	7·5	7·5	6	5·5
Hardness . . . . .	217	213	250	251	220	273
Quenched—						
Bath and temperature . . . . .	air 800°	oil 850°	air 800°	oil 800° reheated at 300°	water 800° reheated at 500°	oil 800° reheated at 500°
Tensile strength . . . . .	155·4	146·5	189	151·5	134	148
Elastic limit . . . . .	133·5	129	188	142·2	122	128
Elongation . . . . .	8	9·5	5	7	6·5	6
Contraction . . . . .	41	51	41	42	47·8	14·1
Shock . . . . .	7·5	6·5	8	6	11	4·5
Hardness . . . . .	396	343·0	410	395	301	425

longer possible to contemplate using them in machine construction, and that it becomes needful to anneal them. Now, under present conditions nothing can be more empirical than such treatment, and it is only when it is absolutely unavoidable that it should be resorted to.

Those steels, therefore, which are incapable of taking air quenching, properly carried out, are devoid of interest for the purposes in hand and should be left alone, the more so as, generally speaking, there is, in the matter of selection, an embarrassing wealth of choice.

*Class IV.—Steels with high Percentages of Nickel, with or without Chromium* (B, C, E, H, K, P, U, V).—The chief obstacles to the development of these steels are of two descriptions:—

(1) The cost of production, which necessarily increases with the increase in the percentage of nickel and with the difficulty experienced in producing metal of such hardness, and in rolling and forging it without any cracks or fissures occurring, and—

(2) The great hardness of the metal even when in a condition in which, from the point of view of service, its properties are at their best.

Indeed it is sought to obtain, in this class of steels, which are, according to the phrase employed by Mr. Guillet, in course of martensitic transformation, steels which may be placed, by reason of their very composition, in the intermediate zone, between pearlite and martensite. Now this zone is very circumscribed, and the least difference in percentage composition becomes the more dangerous as it has the immediate result of making the steel pass over the border of the zone, and of assuming a distinctly martensitic structure which it becomes impossible to alter. The steel will resist the action of the tool, and further, this modification cannot be produced throughout the mass unless the nickel is disseminated very uniformly. At localities where it is in excess the hardness will be greatly increased, to the extent of causing the breakage of the tool during machining. This fact has been established on several occasions.

With steels containing a very low percentage of carbon another phenomenon presents itself, as the result of errors in composition, and having the opposite effect. The steel becomes incapable, on the other hand, of hardening under the customary treatment; quenching in air is, in particular, without result, the influence of nickel alone being insufficient to permit, in the absence of a certain proportion of carbon, of hardness being obtained.

These disadvantages are very serious although not insurmountable, and it is for the manufacturer to surround the manufacture of steels of this type with every requisite safeguard if he wishes to employ a type of steel which, from the

point of view of the applications that may be made of it, is of obvious interest.

The most characteristic of these steels do not, as will be seen from Table V., fall below a tensile strength of 100 kilogrammetres per cubic millimetre, which prevents their being easily machined.

TABLE V.—*Steels of the Fourth Class.*

Steels . . .	B.	C.	E.	H.	K.	P.	U.	V.
Chemical composition—								
Carbon . . .	0.172	0.392	0.157	0.101	0.360	0.477	0.266	0.265
Manganese . .	0.13	0.68	0.48	0.35	0.37	0.95	0.39	0.24
Nickel . . .	15.52	5.19	7.57	5.36	4.20	4.90	4.90	4.40
Chromium . .	nil	0.78	traces	1.75	1.15	traces	0.85	2.33
Transformation points—								
Heating . . .	665°-680°	755°-810°	740°-780°	740°-790°	740°-800°	730°-775°	790°-825°	745°-775°
Cooling . . .	240°-275°	225°-275°	555°-610°	425°-500°	390°-425°	380°	510°-550°	510°-550°
Annealed—								
Temperature . .	503°	600°	800°	600°	600°	600°	750°	900°
Tensile strength .	102	103.5	63.5	115.2	90.2	100	100.2	86.5
Elastic limit . .	84	64.4	42.7	100.5	84.1	85	66	52.8
Elongation . . .	6	14.5	22	13.5	17	12	6.5	5.5
Contraction . . .	43.4	52.8	63.2	58.4	62.4	55	28	9.8
Shock . . . . .	6	6.5	18.5	19	7	10	5.5	9.5
Hardness . . . .	260	268	186	173	225	290	288	232
Quenched—								
Bath and temperature . .	air, 750°	air, 800°	water, 800°	water, 800°	air, 850°	oil, 750°	water, 750° reheated at 500°	water, 850°
Tensile strength .	132.5	... *	122.6	132.2	165.5	205	132	129.5
Elastic limit . .	120.4	...	110.3	118.8	158.8	205	119	112.5
Elongation . . .	11	...	11	10	9	5.6	7	10
Contraction . . .	52.6	...	61.1	56	24.5	38.9	45.7	52.5
Shock . . . . .	9.5	4.5	13	10	7.5	7.5	10	8
Hardness . . . .	364	512	326	286	402	477	300	298

*Steel B.*—This steel contains more than 15 per cent. of nickel and does not even attain a satisfactory result from the point of view of the tensile strength except by thermal treatment at an exceedingly low temperature, which no longer assures to it the possession of its other favourable properties. It is true that its transformation point on cooling is greatly lowered by

\* All the test-pieces broke badly.

its composition, to the extent, even, of  $240^{\circ}$  to  $275^{\circ}$ , and that, no matter what thermal treatment be applied, it is impossible to modify the distinctly martensitic structure which results therefrom. Annealed at  $600^{\circ}$  or  $650^{\circ}$  it constantly gave:—

Tensile strength . . . . .	132.1 kilogrammes.
Elastic limit . . . . .	88.0 „
Elongation . . . . .	11.0 per cent.
Reduction of area . . . . .	49.8 „
Shock test . . . . .	10.0 kilogrammetres.
Hardness number . . . . .	328.

It will be seen, therefore, that besides the softening at  $500^{\circ}$  the elongation has fallen to half (from 11 to 6). This change in the metal is but transitory, and has no influence on the ultimate value of its mechanical properties after a fresh thermal treatment.

This metal should quench normally in air, but in these circumstances it only yields the same results as are obtained by annealing at  $600^{\circ}$  or at  $650^{\circ}$ , no matter what the temperature of reheating may be.

At  $750^{\circ}$  the following results are obtained:—

Tensile strength . . . . .	132.5 kilogrammes.
Elastic limit . . . . .	120.4 „
Elongation . . . . .	11.0 per cent.
Reduction of area . . . . .	52.6 „
Shock test . . . . .	9.5 kilogrammetres.
Hardness number . . . . .	364.

The increase in the elastic limit has certainly some slight importance, but, generally speaking, the steel appears to have attained its maximum tensile strength by quenching in air.

Experiments in water quenching without reheating did not conduce to the development of satisfactory qualities; while after heating, on the contrary, the steel no longer possesses elongation equivalent to that at  $400^{\circ}$ . It is, however, considerably softened and still remains of some interest.

*Steel C.*—The first innovation practised by the firm manufacturing this steel was to lower the percentage of nickel to the neighbourhood of 5 to 6 per cent., so as to obtain a metal situated within the zone of transition to which reference has been made above. In the second place, in order to obtain a steel with greater tensile strength they succeeded, by forcing

up the percentage of carbon, in making steel C, which possesses a cooling transformation point at the same temperature as steel B ( $225^{\circ}$  to  $275^{\circ}$ ), and, like the latter, it should possess the properties of a steel almost entirely martensitic.

This new metal is somewhat curious to study. By reheating, carried out at  $800^{\circ}$ , with a view to obtaining the maximum softening, it yields a tensile strength of 103·5 kilogrammes per square millimetre, whereas at  $500^{\circ}$  only the following properties could be obtained:—

Tensile strength . . . . .	116·6 kilogrammes.
Elastic limit . . . . .	66·6      „
Elongation . . . . .	12·0 per cent.
Reduction of area . . . . .	68·0      „

values almost similar to those which were obtained at the temperature of  $650^{\circ}$ .

As regards quenching it becomes quite impossible to compare the different tests and to give the value of each by any series of figures whatever. Not one of the test-pieces which were broken after quenching in air from different temperatures allowed of single results being obtained; they were all too fragile and broke at the heads owing to torsional strains without having developed their maximum tensile strength. In addition to this the shock tests furnished values varying from 3·5 kilogrammetres to 5·5 kilogrammetres, figures appreciably lower than those considered needful in the case of all other steels held to satisfy the requirements. The hardness, on the other hand, attains the highest values, and by the methods employed in these tests the impressions of the ball become altogether insignificant and difficult to measure with any degree of accuracy. The mean of the determinations yields a hardness number of 512.

No other form of quenching was possible in these circumstances, in which even simple quenching does not answer, and the steels were therefore rejected in advance. Such a steel is, nevertheless, employed by certain builders, and the test pinion and crown wheel furnished an interesting result.

*Steel E.*—This metal possesses properties differing entirely from those of other bodies of this class. It certainly contains 7 per cent. of nickel, but with a very low percentage of carbon



and hardly any traces of chromium, which makes it approximate closely to the very soft steels of the second class, such as steel A, or steel Q.

The temperature of reheating has not much influence on its properties, and as long as the cooling is sufficiently slow there are easily obtained the characteristics indicated in the general table.

Thus, annealed at  $800^{\circ}$ , it gives:—

Tensile strength . . . . .	63.5 kilograms.
Elastic limit . . . . .	42.7 „
Elongation . . . . .	22.0 per cent.
Reduction of area . . . . .	63.2 „

and at  $850^{\circ}$  it gave:—

Tensile strength . . . . .	64.6 kilograms.
Elastic limit . . . . .	39.4 „
Elongation . . . . .	16.0 per cent.
Reduction of area . . . . .	43.5 „

With a metal as soft as this no apprehension need be entertained as regards water quenching. Heated to  $800^{\circ}$  it gives:—

Tensile strength . . . . .	122.6 kilograms.
Elastic limit . . . . .	110.3 „
Elongation . . . . .	11.0 per cent.
Reduction of area . . . . .	61.1 „
Shock test . . . . .	13.0 kilogrammetres.
Hardness number . . . . .	326.

This result is very low and the tests of the gears bore it out. The metal underwent deformation under the pressure of the contact of the teeth, and their engagement at the moment of changing speeds was very seriously impaired after a very few changes. The employment of such a metal is not possible in practice; it is, moreover, not even recommended by the firm making it for this purpose (Fig. 10).

*Steel H.*—With a little less nickel than the preceding, the same percentage of carbon, but nearly 2 per cent. of chromium, this steel should freely quench in air, but it is, at the same time, one of those to which the general statement relative to the susceptibility of these steels to variations in composition specially applies. This fact appears due to its very low percentage of carbon. Directly the latter undergoes the



slightest variation it becomes no longer possible to machine the steel if the percentage increases, or to harden it if the percentage diminishes.

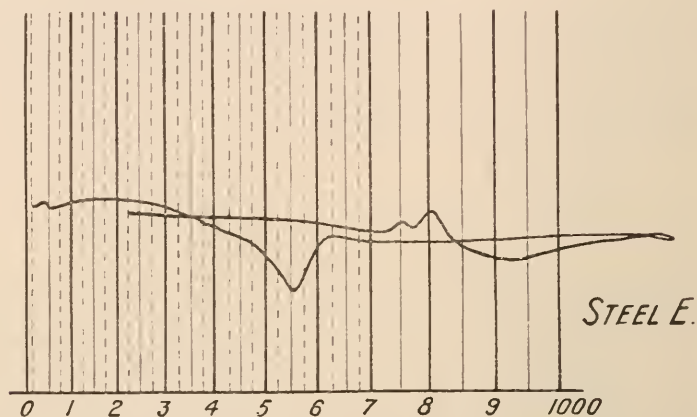


FIG. 10.—Curve for the Determination of the Transformation Points.

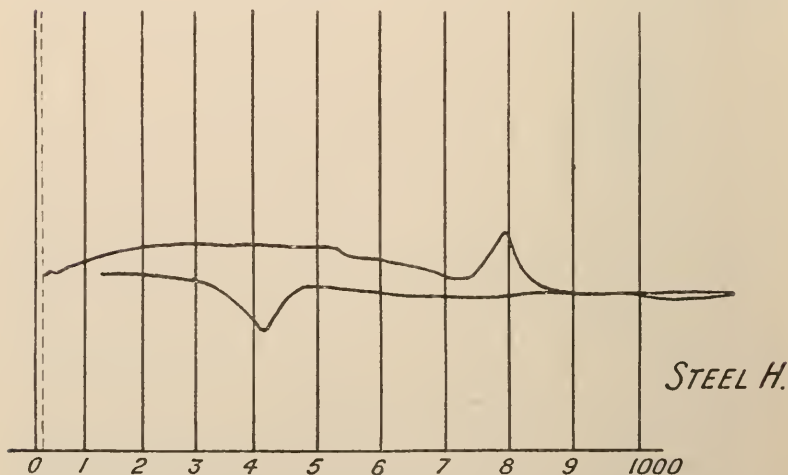


FIG. 11.—Curve for the Determination of the Transformation Points.

The sample which served for the tests corresponds to a metal fairly suitable for the usage for which it is intended; that intended for making the cylindrical rolls for the gears

was a little milder and possessed less hardness after identical treatment.

In addition to the anneal which gave the best result, there was obtained at a temperature of  $650^{\circ}$ :—

Tensile strength . . . . .	164.0 kilograms.
Elastic limit . . . . .	115.0 „
Elongation . . . . .	12.0 per cent.
Reduction of area . . . . .	51.8 „

while the hardness did not reach 300 (298).

The foregoing was similarly the best result which either air quenching or water quenching yielded. In another test, after water quenching at  $800^{\circ}$ , only the following was obtained:—

Tensile strength . . . . .	132.2 kilograms.
Elastic limit . . . . .	118.8 „
Elongation . . . . .	10.0 per cent.
Reduction of area . . . . .	56.0 „
Shock test . . . . .	10.0 kilogrammetres.

The hardness test carried out on a pinion put to work in the testing appliance only yielded  $250^{\circ}$ , which is obviously too low for a steel required to work under conditions of pressure and shock. A distinct space was left between the pinion and the crown, however, in a steel of the same quality. In fine, this metal does not appear the most suitable, as, by its nature, it is in one or other of the pearlitic or martensitic areas, and heat treatment has little effect in altering its properties (Fig. 11).

*Steel K.*—The percentage of carbon and the percentage of chromium react in this instance simultaneously, and in such an efficacious manner as to allow of quenching hardness being developed. Their moderate amounts allowed of the steel being lowered, by a careful reheating, down to 91 kilogrammes per square millimetre, a figure which none of the analogous metals of the same class were able to attain.

A temperature of  $600^{\circ}$  is absolutely necessary. It yields:—

Tensile strength . . . . .	90.2 kilograms.
Elastic limit . . . . .	84.5 „
Elongation . . . . .	17.0 per cent.
Reduction of area . . . . .	62.4 „
Hardness number . . . . .	225.

At 650° there was still obtained:—

Tensile strength . . . . .	130.0 kilogrammes.
Elastic limit . . . . .	84.1     „
Elongation . . . . .	10.5 per cent.
Reduction of area . . . . .	24.4     „
Hardness number . . . . .	326.

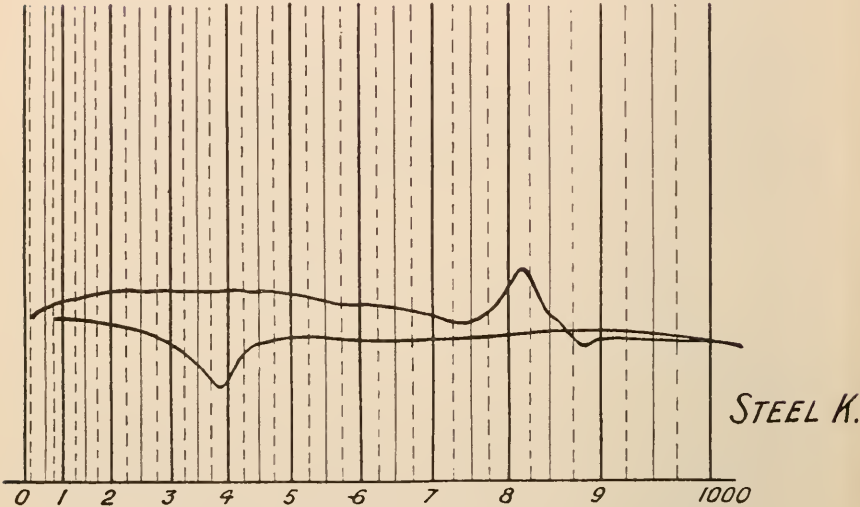


FIG. 12.—Curve for the Determination of the Transformation Points.

Quenching in air seemed fully indicated, inasmuch as the point of transformation on cooling is low (390° to 425°). It gave a number of satisfactory properties:—

Tensile strength . . . . .	165.5 kilogrammes.
Elastic limit . . . . .	158.8     „
Elongation . . . . .	9.0 per cent.
Reduction of area . . . . .	24.5     „
Shock test . . . . .	7.5 kilogrammetres.
Hardness number . . . . .	402.

By having a relatively low tensile strength and preserving a still fairly important elongation there is thus obtained the limit imposed by the previous investigations, with regard to the purpose required, from the point of view of the hardness, namely, a hardness number exceeding 400.

Oil quenching should have a still better effect. A shortage in the supply of this metal unfortunately prevented more complete tests being carried out (Fig. 12).

*Steel P.*—The increase in the percentage of carbon does not have a good effect. The steel can obviously harden considerably; but, on the other hand, softening would only be possible if, at the same time, consent be given to a diminution in the percentage of nickel. If the latter be maintained in the neighbourhood of 5 per cent., as in the present instance, even if the chromium be kept down, the steel will always remain wholly martensitic, and, no matter what the annealing temperature may be, only the following results will be obtained :—

Tensile strength . . . . .	205·0 kilogrammes.
Elastic limit . . . . .	203·0 „
Elongation . . . . .	5·6 per cent.
Reduction of area . . . . .	38·9 „
Shock test . . . . .	7·5 kilogrammetres.
Hardness number . . . . .	477.

This is obviously a good result, but it has been equalled with other steels.

Quenched in air at a temperature of 800° the properties were :—

Tensile strength . . . . .	173·0 kilogrammes.
Elastic limit . . . . .	165·0 „
Elongation . . . . .	6·0 per cent.
Reduction of area . . . . .	38·7 „
Shock test . . . . .	6·5 kilogrammetres.
Hardness number . . . . .	415.

*Steel V.*—Amongst some of his earlier investigations the author had encountered the characteristics of the metal which closely approaches steels of this class in its composition.

Tensile strength . . . . .	100·2 kilogrammes.
Elastic limit . . . . .	66·0 „
Elongation . . . . .	6·5 per cent.
Reduction of area . . . . .	28·0 „
Shock test . . . . .	5·5 kilogrammetres.
Hardness number . . . . .	288.

It possesses, after softening, the most suitable properties, particularly from the point of view of the elongation and resistance to shock. This steel displays very indifferent qualities, which prevented its undergoing quenching without

subsequent annealing. In these circumstances it gave, quenched in water at  $750^{\circ}$  and annealed at  $500^{\circ}$ :—

Tensile strength . . . . .	132.0 kilogrammes.
Elastic limit . . . . .	119.0 „
Elongation . . . . .	7.0 per cent.
Reduction of area . . . . .	45.7 „
Shock test . . . . .	10.0 kilogrammetres.
Hardness number . . . . .	360.

Despite the difference in the points of transformation ( $500^{\circ}$  to  $800^{\circ}$ ) there was obtained, on air quenching from  $800^{\circ}$ , only the following results:—

Tensile strength . . . . .	122.3 kilogrammes.
Elastic limit . . . . .	73.4 „
Elongation . . . . .	3.5 per cent.
Reduction of area . . . . .	5.7 „

#### CASE-HARDENING TESTS.

As the questions which the experiments were sought to elucidate bore, on the one hand, on the ease of working the metal before any treatment, and, on the other hand, on the hardness of the parts after as simple a quenching as possible, it was natural to think of employing one of the soft steels experimented upon, of good quality and capable of developing sufficient tensile strength by quenching, and of correcting the insufficient surface hardness by an addition of carbon, or in other words, to combine together the best of the qualities of steels of the second and third classes without perpetuating their defects.

Unfortunately mechanical tests of case-hardened pieces, in practice, amount to very little importance. It is no longer practicable to apply the Brinell ball hardness test in order to ascertain the hardness with accuracy. The only conclusion to be drawn from this test is the evidence of an increase in the superficial hardness, without its being safe to express, in figures, the equivalent value of this increase. The principal test after case-hardening consists of examining the grain and proving the non-brittleness of the core treated, and the strength of the exterior layer under the influence of slight local shocks not producing the fracture of the piece. Gener-

ally speaking, a harder quenching may be conferred than the outer layer would ordinarily stand owing to its composition, as the core contributes to the strength of the periphery. In this case, by oil quenching a steel which contains, in addition to a sufficient proportion of the elements nickel and chromium, a proportion of carbon approaching 0·6 to 0·8 per cent., very considerable surface hardness can be obtained.

The case-hardening does not require to be taken as far as 1 per cent. of carbon, as in the case of ordinary steels; besides which, as nickel hinders the phenomenon, it would be necessary to heat the piece for a prolonged period, which might be prejudicial to the maintenance of the structure of the core. A few tenths of a millimetre in depth suffice, and can be attained in two to three hours at a temperature of  $800^{\circ}$  to  $900^{\circ}$ . After case-hardening it is preferable to cool slowly, and to quench the pieces after having heated them up again. The determination of the best temperature for quenching leaves a fairly wide margin, as it is impossible to foresee the properties exactly. It is necessary to rest content with the appearance of the fracture, which varies but slowly. It is possible to effect a single quenching both for the core and the surface by carefully choosing the interval common to the temperatures of treatment for steels of extremes in composition. This temperature as a rule oscillates between  $700^{\circ}$  and  $750^{\circ}$ .

A few experiments were made by choosing the best steels of Class II., which were incapable of hardening sufficiently on water quenching. For these purposes the steels A and Q were employed. After three hours' case-hardening at  $300^{\circ}$  there was found, in the case of steel A, an increase in carbon for a depth of 0·3 millimetre. The fracture, after bending almost completely over, and opening out nearly straight again, was remarkably good.

It is possible, under these conditions, to water quench the steels within a very wide range of temperature ( $650^{\circ}$  to  $900^{\circ}$ ), but the best surface hardness is obtained in the neighbourhood of a temperature of  $750^{\circ}$ .

With steel Q the experiments lead, on an average, to the same conclusions. After two hours a slight case-hardening is



obtained, but in practice this increase in the percentage of the carbon becomes quite sufficient to increase the hardness after quenching. The firm making this steel even favour the dissemination of the carbon introduced at the surface by a somewhat prolonged reheating at a point slightly below that of transformation, but this operation did not yield very distinctive results on subsequent micrographic examination.

Amongst the steels which were advantageously case-hardened must also be enumerated steels H and E. The former, in particular, which does not harden sufficiently on air quenching in the ordinary condition owing to its percentage of carbon being too low, becomes, on the contrary, martensitic at once, even without any further quenching, if it be slightly carburised on the surface. The hardness appears absolutely comparable to that of the best samples, and the treatment is simple, it being sufficient to pack it in the box with the cementing powder, and to withdraw the pieces while still hot after heating for two hours at  $800^{\circ}$ . By taking certain precautions this treatment produces no greater deformation than the ordinary air quenching.

These experiments were not continued on other steels, and the author regrets he was unable to employ an apparatus capable of ascertaining the increase in the surface hardness, such, for instance, as a scratching sclerometer, the tests by which act only on the surface, or on a very slight depth.

### TESTS OF GEARS.

The following shows the latest results of the researches carried out by means of the arrangement described at the commencement of this report, for the pinions and crown wheels arranged on an ordinary speed change appliance. The pieces which have passed the test up to the present were made from the following steels:—

A. Water quenched at $750^{\circ}$	N. Air quenched at $800^{\circ}$
C. Air " $650^{\circ}$	O. { Oil " $850^{\circ}$
E. Water " $800^{\circ}$	{ Annealed at $250^{\circ}$
H. " " $800^{\circ}$	X. { Oil quenched at $825^{\circ}$
K. Air " $850^{\circ}$	{ Annealed at $500^{\circ}$

All the soft steels, such as A, E, and H, showed very con-

siderable wear, not only on the crown of the teeth, but also on the sides, as the results of the shocks which occurred when they were thrown into clutch.

With steel O there appeared to have been but slight wear on the facets of the teeth, but, as with the preceding results, the edges of the teeth at the points of entry were badly damaged, even after only six successive clutchings had been made.

The manganese steel of series X did not behave badly, but it was the first tested, and no attempt had then been made to throw the gears in and out of clutch while running. The wear on the faces of the teeth was approximately the same as in the case of steel A.

Finally, steels C, K, and N behaved much better. N in particular showed but a slight burnishing effect at the contact surfaces without the least trace of wear, particularly as regards the crown wheel. If to this test be added the simplicity of the treatment it requires, this metal should be classed amongst the best of those which were subjected to the experiments.

#### CONCLUSIONS.

These facts, taken in connection with the foregoing results, permit of the deduction of the following conclusions:—

1. It is possible to find, amongst either class of sample, a steel more or less suitable for use in making gears.

2. Steels not containing nickel are commercial products which can be obtained at low cost, and can be made, after treatment, to give hard gears, but have relatively a high degree of brittleness. They have been much in favour, but they require complicated heat treatment, and manipulation closely adjusted to their composition.

3. Soft nickel steels quenched in water are insufficiently hard, but they are susceptible of being case-hardened and then furnish products of superior quality.

4. With an increasing percentage of carbon it is possible to find steels quenching in oil or in air, the properties of which as regards resistance to shock, and the elongations of which are increased by the presence of nickel.

5. When the percentage of nickel is increased it is possible to obtain, with a well-adjusted carbon percentage, a steel which, with a simple treatment, will yield the best results.

Annealing should, however, be very carefully conducted in order to soften the metal well for the purpose of machining, while after having completely finished the piece, air quenching will suffice to insure good hardness and good resistance to shock.

The great defect of these steels is their extreme sensitiveness to the smallest variations in composition. They require the greatest watchfulness in the metallurgical works in order to yield the results one is justified in expecting to obtain. The most minute error in their percentage composition has the effect of rendering them either incapable of being worked, in the case of an increase in the nickel and the carbon, or of preventing them from being hardened on air-quenching. In this latter case there is always the alternative of quenching them in oil, but one is no longer secured against deformation on quenching, as is the case when they are quenched in air. Their cost of production is also a great obstacle to the development of their employment in mechanical construction.

6. Apart from the steels of the first class, for which a complicated heat treatment is necessary, it is always possible to find, amongst nickel steels, a steel corresponding in properties to all the requirements of a specific manufacture and requiring but simple treatment, that is to say, capable of being used after simple quenching without subsequent annealing—annealing being from the industrial point of view impossible to define scientifically, and difficult to adjust uniformly from one piece to another when the volume of the piece is altered.

## V.

# GASES OCCLUDED IN STEEL.

BY THOMAS BAKER, M.Sc., M.Met., F.I.C. (LLANELLY).

### INTRODUCTION.

It is well known that metals in both the solid and liquid state possess the property of absorbing quantities of gas which are often far from being negligible, and several researches have already been published on the subject.

Graham, by heating *in vacuo* various specimens of iron, and collecting the gases evolved, first proved the existence of hydrogen, carbon monoxide, carbon dioxide, and nitrogen in solid iron; his experiments were afterwards repeated by Parry, who found that the gases evolved from wrought and cast iron consisted essentially of carbon monoxide and hydrogen, the latter always being in excess in the first portions of the gas given off at a low temperature. Nitrogen, although repeatedly sought for, was found only in quantities within the limits of experimental error. Parry is also of the opinion that some of the carbon monoxide may be due to reaction between the carbide of iron and the silica of the porcelain tube. The large volumes of hydrogen and carbon monoxide obtained by him, however, have rendered his results open to the suspicion that the whole of the gases could not have been obtained from the steel, but must have come in part from some portion of the apparatus employed in the experiment.

By drilling steel under water or mercury, Stead and Müller have collected considerable quantities of hydrogen and nitrogen, the quantity obtained being very much greater—in one case fifty times as great—when the steel was finely comminuted

with a blunt drill, than when it was cut by a sharp tool. The relation of the volume of hydrogen to that of nitrogen, however, remained the same in the two cases.

After a series of very careful investigations, Troost and Hautefeuille arrived at the following conclusions:—

(1) Whenever iron is maintained in the molten condition in contact with silica or silicates, oxide of carbon is evolved, resulting from the action of the carbide of iron on the silica.

(2) Molten cast iron dissolves notable quantities of hydrogen; silicon greatly diminishes the solubility of hydrogen; manganese, on the other hand, augments it considerably.

(3) Oxide of carbon is much less soluble than hydrogen; the presence of manganese diminishes the solubility of this gas, and may even prevent it.

(4) Cast irons after solidification retain gases, which may be extracted by heating them to a temperature not exceeding  $800^{\circ}$  C.; above this temperature reactions are produced among the elements present. Hydrogen in the solid as in the liquid metal is in much greater quantity than oxide of carbon, and is more energetically retained than the latter. Cast irons high in manganese retain more hydrogen than those which are low in manganese.

(5) Steel dissolves much less gas than cast iron; hydrogen is contained in greater proportion than oxide of carbon, and is also, as in the case of iron, much more energetically retained.

(6) Soft iron dissolves, on the contrary, more oxide of carbon, which is retained with the greatest energy.

Boudouard, by heating merchant iron and iron wire, and collecting the gases given off, has shown that the quantities of the latter are of the same order as those of the sulphur and phosphorus present in the iron.

The latest work on the subject is that of Belloc, who has studied the relation between the temperature and the rate of evolution of gas from a very mild steel ( $C=0.12$  per cent.;  $Mn=0.35$  per cent.), and has found that the evolution of gas is in strict relation to the critical points of the steel; he also notes that at the lower temperature the gas evolved is almost



entirely carbon dioxide, above  $400^{\circ}$  C. hydrogen and carbon monoxide; about  $550^{\circ}$  carbon dioxide disappears. Above this temperature nitrogen appears, but its volume does not exceed 10 per cent. of the total volume of the gas. Belloc concludes that a dissociation temperature of the gases is improbable.

Little is known of the effect of these gases upon the physical properties of iron and steel, apart from mechanical defects, such as blowholes, produced by their presence, and a peculiar kind of brittleness due to "pickling," which can be removed by annealing.

Blowholes can, of course, to some extent be eliminated by the addition of small amounts of silicon and aluminium to the molten metal before casting. Pourcel has asserted that blowholes are due to the evolution of carbon monoxide from the reaction between the carbon and the oxide of iron present in the steel, and has explained the action of silicon or aluminium by the fact that at the temperature of molten steel they have a greater affinity for oxygen than has carbon; they therefore replace it in the reduction of the oxide of iron, and might even reduce any carbon monoxide present in the molten steel.

Dr. Müller, on the other hand, puts forward the following hypothesis:—In the liquid state the metal dissolves carbon monoxide, hydrogen, and nitrogen, and as the temperature falls, the solubility of the gases decreases, the gases having a tendency to escape in the following order: 1st, carbon monoxide; 2nd, nitrogen; and 3rd, hydrogen; when the second and third escape, however, the metal has begun to solidify, hence the formation of blowholes. In order to explain the delay in the evolution of nitrogen and hydrogen, he assumes the formation of definite compounds of the gases with the molten metal.

These theories have been modified by M. Le Verrier, who states that the molten metal maintains hydrogen and nitrogen dissolved in a state of supersaturation; anything which tends to destroy this state of false equilibrium, such as the evolution of carbon monoxide, results in the liberation of the other two gases. Thus silicon or aluminium, by preventing the formation of carbon monoxide, tend to the production of sound steel.



## OBJECTS OF THE RESEARCH.

The object of the present research was—

(a) To ascertain the nature and volume of the gases given off when steel is heated *in vacuo*.

(b) To find the relation (if any exist) between the critical points of the steel and the extent of the evolution of the gas.

(c) To discover the part played by these gases in the production of blowholes.

Equal quantities of converted bar were melted in two crucibles in the same coke-fired furnace. To one was added a small quantity of aluminium, and each was cast in a cast-iron

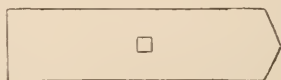


FIG 1.

mould 6 cubic centimetres square. As one would expect from the method of preparation, one of the ingots thus obtained was perfectly sound, while the other was full of blowholes.

The chemical analysis gave the following results:—

	Per Cent.	Per Cent.
Combined carbon . . . . .	0·810	0·900
Silicon . . . . .	0·080	0·088
Manganese . . . . .	0·050	0·096
Aluminium . . . . .	...	0·033
Sulphur . . . . .	0·028	0·023
Phosphorus . . . . .	0·019	0·019
Iron (by difference) . . . . .	99·013	98·841

From each of these ingots a piece 6 centimetres long and 1 square centimetre sectional area was cut out in the position indicated in Fig. 1 and filed up smooth, and a hole was drilled in one end for the reception of the thermo-couple.

Throughout the whole of the machining every possible precaution was taken to guard against the contamination of the samples with oil.

## APPARATUS EMPLOYED.

The apparatus used for the extraction of the gases consisted of (*a*) a porcelain tube glazed internally and externally, and closed at each end by rubber stoppers. Through one of these passed a glass tube, making connection with (*b*) a Toepler mercury pump, and through the other two glass tubes passed into which the leads of the thermo-couple were fused. This stopper also afforded an easy means of introducing the steel under examination into the tube. The tube was heated by means of (*c*) an electric resistance furnace, the rheostat of which allowed any fixed temperature to be maintained, with

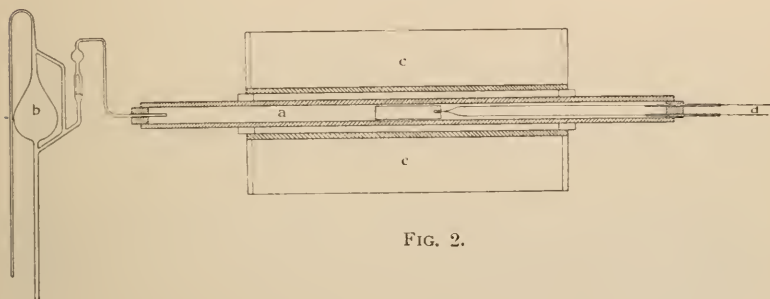


FIG. 2.

slight variations, throughout the period of heating. In order to prevent undue heating of the rubber stoppers, the ends of the tube were water-cooled.

The temperatures were determined by (*d*) a carefully calibrated millivoltmeter used in connection with a platinum platinum-iridium thermo-couple.

The general arrangement of the apparatus is shown in Fig. 2.

In the first set of experiments (when a gas furnace was employed for heating the tube) the presence of methane was noticed in the gases extracted. It was thought possible that this might be due to the diffusion of gas from the furnace, and a blank determination, lasting three days, was made on the apparatus (tube, stoppers, and thermo-couple); 1.29 cubic

centimetre of gas was collected, of the following percentage composition:—

	Per Cent.
Hydrogen . . . . .	52·7
Carbon monoxide . . . . .	7·8
Marsh gas . . . . .	20·9
Nitrogen . . . . .	18·6

As this seemed to bear out one's suspicions, an electric furnace was substituted, and another blank determination, lasting nine days, was made, the gas being drawn off and analysed every third day. The results were as follows:—

TABLE I.

	Volume in Cubic Centi- metres.	CO <sub>2</sub> .	H <sub>2</sub> .	CO.	CH <sub>4</sub> .	N <sub>2</sub> .
First period . . . . .	0·84	15·48	40·00	...	19·05	25·47
Second „ . . . . .	1·15	18·25	52·20	11·22	5·48	12·78
Third „ . . . . .	1·18	4·23	73·22	13·55	5·93	3·13

From these results it appears immaterial whether the tube is heated by gas or electricity. The only other apparent source of error was in the rubber stoppers used to close the ends of the tube; half-a-dozen of these, therefore, were heated in a vacuous flask at 100° C., a temperature higher than that of the ends of the tube in an actual experiment, but they yielded only a few cubic centimetres of air at the end of three days.

By a process of elimination, then, the conclusion is arrived at that either the porcelain tubes or the thermo-couple, or both, give off a small volume of gas when heated in vacuo, and in this connection it may be well to note that Fox (Thesis for the Master's Degree in Science, Massachusetts Institute of Technology) found that thoroughly dried oxygen, when swept through an otherwise empty red-hot porcelain tube, persistently yielded small quantities of water—3·5 milligrams during the first hour, 0·7 milligrams from the twelfth to the fourteenth hour. No correction has been made for this in the appended results.

After the thermo-couple had been inserted in the small hole drilled in the end of the test-piece, the whole was pushed into the tube and the stopper inserted. The tube was exhausted by means of the mercury pump, and the vacuum maintained for forty-eight hours before starting the actual experiment; this was found necessary to remove the thin film of air which persistently clings to the walls of the tube and the surface of the specimen. Even after taking this precaution the gases first drawn off often contained small quantities of nitrogen.

The extraction was continued over ten days, the period of heating being eleven hours per day; at the end of each day the gas was collected and analysed. The temperature of extraction, and the volume and composition of the gas extracted are given in Table II.

TABLE II.

Tem- perature of Extraction.	Steel without Blowholes. Weight taken, 69·31 grams.										
	Volume in Cubic Centimetres.						Composition.				
	Total.	CO <sub>2</sub> .	H <sub>2</sub> .	CO.	CH <sub>4</sub> .	N <sub>2</sub> .	CO <sub>2</sub> .	H <sub>2</sub> .	CO.	CH <sub>4</sub> .	N <sub>2</sub> .
Degrees C.							Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
519	6·53	0·07	6·37	0·07	0·02	0·00	1·07	97·54	1·97	0·30	0·00
600	10·67	0·19	8·44	2·00	0·07	0·00	1·78	79·10	18·74	0·65	0·00
672	12·87	0·35	8·07	4·40	0·07	0·00	2·71	62·79	34·18	0·54	0·00
688	22·91	0·75	6·96	15·02	0·12	0·03	3·27	30·38	65·56	0·52	0·13
719	12·61	0·07	4·74	7·72	0·06	0·01	0·55	37·58	61·22	0·47	0·08
765	6·71	0·02	3·35	3·26	0·05	0·02	0·29	49·92	48·58	0·74	0·29
802	4·29	0·00	2·24	1·97	0·08	0·00	0·00	52·21	45·92	1·86	0·00
862	4·59	0·05	2·24	2·22	0·08	0·00	1·08	48·80	48·36	1·74	0·00
936	5·04	0·03	2·53	2·42	0·07	0·00	0·59	50·19	48·01	1·38	0·00
979	5·64	0·01	2·83	2·75	0·04	0·01	0·17	50·17	48·75	0·70	0·17
Total	91·86	1·54	47·77	41·83	0·66	0·07	...	...	...	...	...
Steel with Blowholes. Weight taken, 63·261 grams.											
530	3·28	0·09	3·04	0·06	0·05	0·04	2·74	92·68	1·82	1·52	1·22
603	2·96	0·06	2·70	0·08	0·06	0·06	2·02	91·21	2·70	2·02	2·02
681	4·36	0·06	2·16	2·01	0·15	0·03	1·37	48·39	46·10	3·45	0·69
696	5·45	0·02	1·49	3·85	0·05	0·04	0·36	27·34	70·64	0·91	0·73
720	5·04	0·03	1·84	3·11	0·06	0·00	0·59	36·50	61·70	1·19	0·00
762	3·80	0·02	1·87	1·81	0·09	0·01	0·52	49·21	47·63	2·37	0·26
825	3·98	0·02	2·01	1·87	0·07	0·01	0·50	50·50	46·98	1·75	0·25
893	4·24	0·03	2·18	1·93	0·10	0·00	0·71	51·41	45·51	2·35	0·00
944	4·48	0·02	2·32	2·08	0·05	0·01	0·45	51·78	46·42	1·11	0·22
1016	4·50	0·02	3·38	1·05	0·05	0·00	0·44	75·11	23·33	1·11	0·00
Total	42·09	0·37	22·99	17·85	0·73	0·20	...	...	...	...	...

In the case of the unsound steel, as many as possible of the blowholes were cut open, in order to allow the gases contained to escape; the object of the author being to obtain the gases from the solid portions of the steel, leaving that contained in the blowholes for a future investigation.

### CONSIDERATION OF THE RESULTS.

In considering these results, it is of importance to note that they have been obtained on steel as cast, and not on material which has been subjected to further treatment, such as reheating or rolling; processes which may bring about changes both in the quantity and the nature of the gases occluded.

Hydrogen and carbon monoxide form the major portion of the gases evolved on heating in vacuo; carbon dioxide and nitrogen only amounting to 2 or 3 per cent. of the total. An actual analysis of the gases drawn off from a piece of the steel free from blowholes, when heated for thirty-six hours at a temperature of  $1000^{\circ}$  C., is as follows:  $\text{CO}_2$ , 0.48 per cent.;  $\text{H}_2$ , 49.62 per cent.;  $\text{CO}$ , 48.05 per cent.;  $\text{CH}_4$ , 0.40 per cent.;  $\text{N}_2$ , 1.45 per cent.; the small amount of nitrogen present is rather unexpected, as in the work of other experimenters fairly large proportions of this element have been obtained, except in the case of Parry, whose results have already been referred to. Repeated tests on the steels experimented on by the author have, however, resulted in no increase of the percentage above mentioned.

The presence of methane is unusual, and is to some extent accounted for by the gases given off from the porcelain tubes employed, although in certain cases this does not account for the whole of it. It may be due to some reaction taking place between the gases and the carbide of iron present in the steel, as the small porcelain tubes used to insulate the platinum leads of the thermo-couple, inside the vacuous porcelain tube, were always covered with a slight deposit of carbon, although the precaution was taken of heating them to over  $1000^{\circ}$  C. before beginning an experiment.

In the experiments on the sound steel, it was found that hydrogen was given off at as low a temperature as  $300^{\circ}$  C.,

the rate of evolution reaching a slight maximum at  $600^{\circ}\text{C}.$ , and then gradually falling off until a temperature of  $900^{\circ}\text{C}.$  is reached, when it again slowly rises with the temperature; this gas comprises over 90 per cent. of the total gas evolved up to a temperature of  $500^{\circ}\text{C}.$

At this point carbon monoxide begins to be given off; its rate of evolution gradually increases until a temperature of  $690^{\circ}\text{C}.$  is reached, when it is so great as to cause a well-marked maximum. After passing  $690^{\circ}$  the evolution falls off, and reaches a minimum at  $800^{\circ}$ ; it then gradually increases with the rise in temperature, as in the case of hydrogen.

At temperatures higher than  $760^{\circ}$ , the gases given off consist of almost equal quantities of hydrogen and carbon monoxide. The total volume of gas given off amounted to 91.86 cubic centimetres, equal to 10.4 times the volume of the steel employed.

Similar changes were observed in the gases given off from the unsound steel. The total volume of gas given off amounted to 42.09 cubic centimetres, equal to 5.2 times the volume of the steel.

From the curves given in Fig. 3 it will be noticed that the maximum of gas evolution coincides with the  $\text{Ar}_{1,2,3}$  point for both steels, only differing in magnitude, as it is much greater in the case of the sound steel. The increase in the gas given off at  $690^{\circ}\text{C}.$  is due to the evolution of carbon monoxide, as the hydrogen has already passed its maximum.

In the present state of the investigation it is not clear whether the evolution of carbon monoxide is due to the inferior solubility of this gas in  $\gamma$ -iron or to the decomposition of a chemical compound of carbon monoxide and iron.

The influence of aluminium in preventing blowholes seems to be due to the fact that it prevents the liberation of gas during the period of solidification, and not to any action it may have in hindering the production of carbon monoxide; unless, of course, the quantities of this gas obtained in the experiments have been derived from a reaction between the carbide of iron and the silica of the porcelain tubes employed. This, however, does not appear to be the case, as the quantity



of carbide in actual contact with the tube would be approximately the same in both experiments, and in consequence the

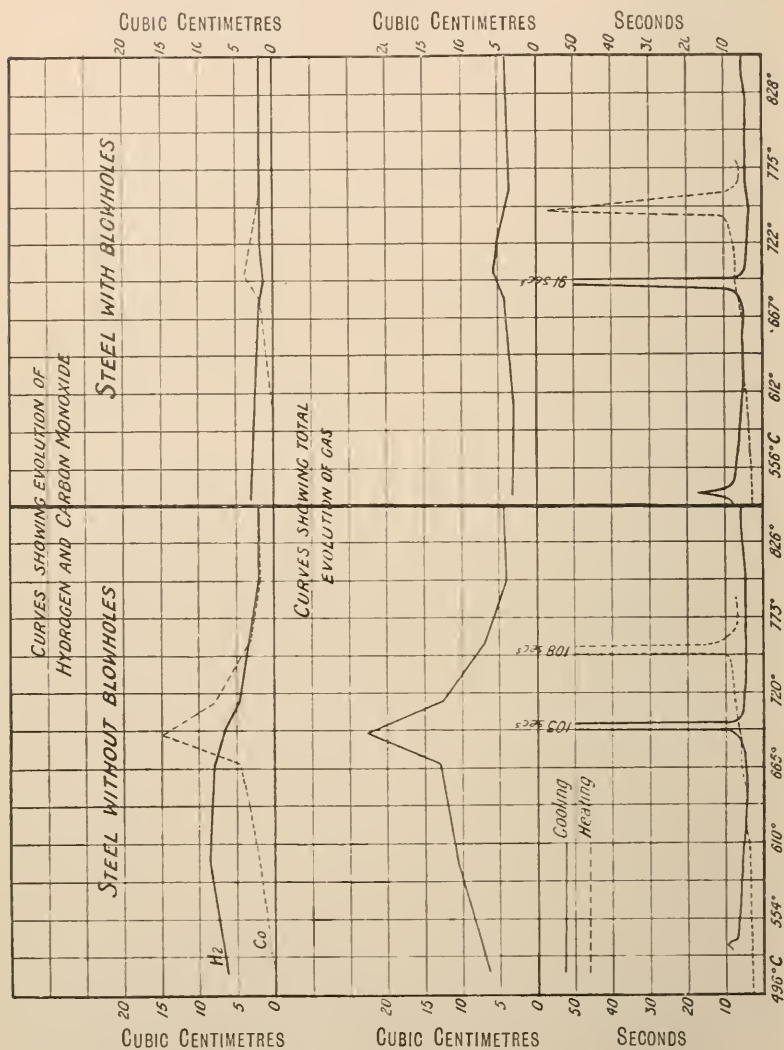


FIG. 3.

volumes of carbon monoxide should be equal. This was not so.

The thanks of the author are due to Professor Arnold for much kindly advice; to Messrs. B. Howell & Sons, Ltd., Llanelly, for the supply of electric power; to J. C. Howell, Esq., for the use of electrical apparatus; and to Messrs. The Glanmor Foundry Co., Llanelly, for the supply of the castings used.

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## VI.

# CONTRIBUTION TO THE STUDY OF THE SPECIAL TERNARY STEELS.

BY ALBERT M. PORTEVIN (PARIS).

### INTRODUCTION.

THIS research comprises two totally distinct portions:—

1. *The application of shearing tests to the special steels* with the object of ascertaining the influence of the elements added on the results of these tests, and of examining their relation to tensile tests, and, in particular, of ascertaining the applicability of the formulæ propounded by Frémont.

2. *A study of the electrical resistance of the special steels*, and the investigation of the influence on this physical property of the chemical composition of the steel, its micrographic structure, and quenching.

Supplementing this second part are two appendices embodying studies of minor importance:—

(1) The influence of vanadium on the transformation-points of steels; and

(2) The influence of titanium on the transformation-points of steels.

### PART I.

## GENERAL CONSIDERATIONS REGARDING SHEARING TESTS.

### 1. PRINCIPLES: FRÉMONT'S FORMULA.

As Frémont has shown, the phenomena of rupture by shearing is a proceeding involving tensile stress, and not one of gliding, as Vicat, who admitted that cohesion was overcome

by a tangential force; that is, without oblique or normal work in the plane of fracture, believed. Each layer compressed by the blade of the shear does not separate immediately from the layer it comes from; there remains a ligament analogous to the portion in a tensile test-piece which becomes elongated under the action of the tool, the lateral disaggregation extends over a zone the depth of which is very nearly equal to the thickness of the piece undergoing shearing or punching. These facts have been demonstrated by Frémont by means of a macrographic research on structural steels; the deformation may similarly be seen under the microscope when two well-defined constituents are concerned, as in the forgeable bronzes. Fig. 1 affords an example of what may be observed in this way after the commencement of the tearing asunder by shearing of a bronze of this description; there may be seen very distinctly the elongation of the constituents prior to rupture. The central portion of the test-piece appears much less affected; it has, nevertheless, undergone a distinctly noticeable deformation, which also reveals itself, as may be particularly seen on the left-hand border of Fig. 1, by pointed projections which appear to be due to the protrusion of the angles of the distorted crystals.

From the point of view of tensile strength, it is necessary to discriminate between double shearing, in which the blade acts on a piece supported at its two extremities, and single shearing, in which the piece is supported at one extremity only. The earlier experimentalists—Ed. Clarke, Mathieu, and Lavallée, and, more recently, Izod—made use of the method of double shearing, under the impression they were approximating more nearly to the theoretical shearing in which there are involved but one plane of sliding and lateral deformation of but little depth. Frémont has shown that the phenomena accompanying rupture was, in this instance, far more complex; for, instead of eliminating the accompanying friction due to the rubbing of the portion carried forward on the cutting blade, it is increased, and, owing to the bending of the piece, an oblique compression is induced, which adds itself in part to the tensile stress of the shearing.

By having recourse to single shearing, on the contrary,



FIG. 1.—Shear Section of a Bronze. Magnified 50 diameters.

Frémont demonstrated that, in structural steels, there was a linear relation between the tensile strength  $R_T$  and the resistance to shear  $R_C$ , and he has given the following formula combining these two quantities:—

$$R_T = \frac{R_C - 7.5}{2.34}.$$

The elastic limit  $E_C$  on shearing may be determined with as much accuracy as the elastic limit of tensile strength  $E_T$ . Frémont found that

$$E_C = \frac{4}{10} E_T.$$

With regard to the ductility of the metal, the shearing test permits of the contraction  $\frac{s-s'}{s}$  being ascertained by measuring, as will be seen later, the distance  $\sigma$  of the maximum ordinate from the starting-point of the diagram.

## 2. OBJECT OF THIS INVESTIGATION.

In addition to the variations in resistance to shearing stresses conferred by the admixture with the steel of special elements, the study of which is of obvious utility, it was of interest to ascertain the influence of the structural alterations which may be observed in special steels, and to see whether the relation between the data yielded by the tensile tests and those given by shearing tests would continue constant, despite the specific influence of the added metal and of the structural alteration—or, in a word, to establish whether Frémont's formula could be applied in this instance likewise.

The triple objects thus proposed for solution were, therefore:—

1. To study the variations in the resistance to shearing\* by the addition of special elements to the steel.
2. The relation between the constants of shearing-stress tests and the micrographic structure of the steel; and
3. The relation between the constants of the tensile tests

\* This phrase, "resistance to shearing," is henceforth to be taken as connoting the three constants of such resistance, tensile strength, elastic limit, and contraction.



and those of the shearing-stress tests, and, in particular, the verification of Frémont's formulæ.

### 3. EXPERIMENTAL ARRANGEMENTS.

(a) *Apparatus*.—The apparatus employed was that of Frémont (Fig. 2), which has been described elsewhere.\* This apparatus, as is well known, is furnished with a cylindrical

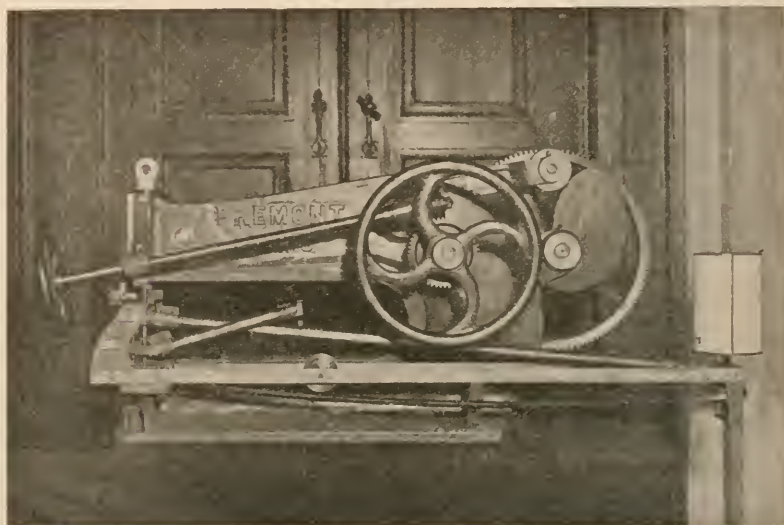


FIG. 2.—Frémont Apparatus.

recorder, the rotational movement of which—corresponding to the abscissæ of the diagram—is actuated by the amplified lowering of the blade of the upper shear, and of which the ordinates represent the deformations of the bedplate of the machine, considerably multiplied. Given the section of the bedplate, these deformations are proportional to the stresses. The abscissæ of the diagram are therefore proportional to the deformation undergone by the piece and the ordinates to the shearing stress.

(b) *Test-pieces*.—Owing to the great resistance of some of

\* *Bulletin de la Société d'Encouragement*, September 1901.

the steels employed, the test-pieces for shearing tests, the section of which had been originally selected at 8 millimetres by 10 millimetres, were reduced to 6 millimetres by 8 millimetres, while, owing to the hardness of a large number of the samples, the work of shaping the test-pieces was wholly carried out by means of the emery wheel. In order to

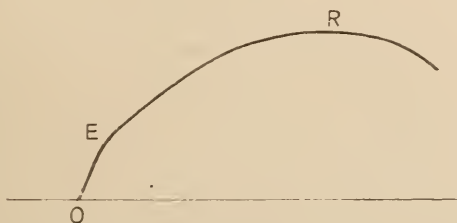


FIG. 3.

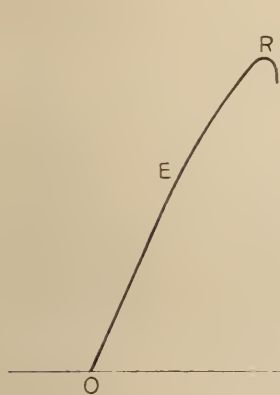


FIG. 4.

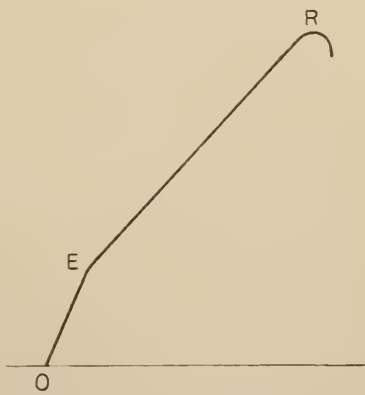


FIG. 5.

destroy the effects of cold working, and also, in certain instances, the state of quenching, all the test-pieces tested were reheated in pig-iron siftings (in order to avoid decarburisation), for three hours at  $850^{\circ}$ .

#### 4. SHEARING DIAGRAM.

The apparatus registers automatically the diagrams, the general appearance of which is shown in Figs. 3, 4, and 5.

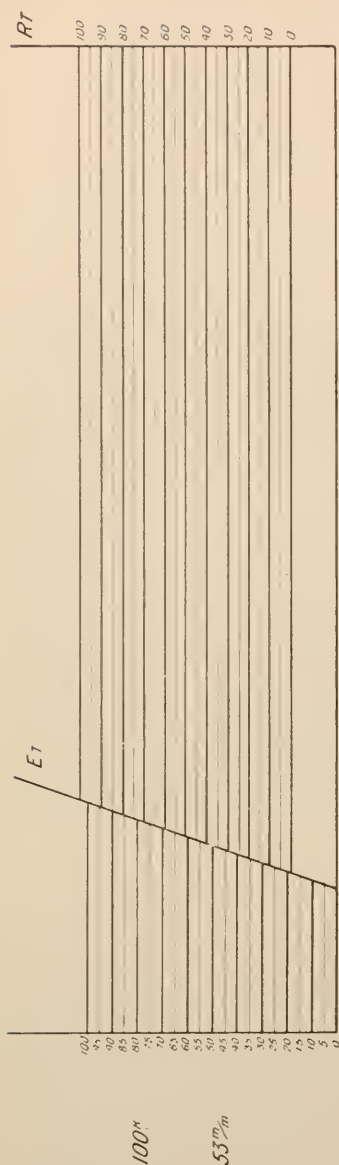


FIG. 6. —Resistance to Shear, 1 kilogramme by 1 cubic millimetre. Test-piece, 6 inches by 8 inches.

As in the diagrams of the tensile tests, the elastic limit is indicated by a sudden change in the direction of the curve and its departure from the rectilinear form, the length of the maximum ordinate of the curve gives the resistance to shear, and the abscissa corresponding with this maximum (the ordinates being traced parallel to the original direction of the curve) is a function of the ductility measured as contraction of area. This abscissa will be distinguished as  $\sigma$ .

The results of the application of Frémont's formulæ can be read direct by means of a vernier scale.

Thus, Fig. 6 gives the scale corresponding to a section of the test-pieces of 6 millimetres by 8 millimetres. This vernier scale is traced on transparent paper and applied to the diagram.

## 5. ACCURACY OF THE RESULTS OBTAINED.

The form of the diagram varies in a noteworthy manner for all the steels, and without seeking to foreshadow the conclusions of the research, one

may, even here, distinguish three types (Figs. 3, 4, and 5), which appear associated with the structure of the steel.

Generally speaking, Fig. 3 shows the appearance of the curves corresponding with pearlitic steels, or steels containing  $\gamma$ -iron. Fig. 4 corresponds more particularly with martensitic steels, and Fig. 5 has been observed with certain  $\gamma$ -iron steels containing manganese.

The greater or lesser accuracy of the readings is directly connected with the form of these curves. Indeed, from the graphic point of view, the intersection of a right line with a curve can be ascertained with the greater accuracy the wider the angle of approach. Now  $E_c$ , which is indicated by the bend which marks the termination of proportional elongation, will be the better ascertained the more accentuated the change of direction. In the same regard, the contact-point of a curve with its tangent can be the more accurately located the smaller the radius of curvature at the point of contact. Thus  $\sigma$ , which is fixed by the position of the maximum ordinate, which is itself distinguished by the point of contact of the curve with its horizontal tangent, will be the more accurately located the more acute the curvature at this point.

$R_c$  is always measured with the same accuracy, except in the case of abnormal fractures. It may be seen that  $E_c$  is well defined in Figs. 3 and 5, and that  $\sigma$  is well defined in Figs. 4 and 5. It may be said that  $E$  is the more accurate the larger  $\sigma$  becomes, and that  $\sigma$  is the more accurate the larger  $R_c$  becomes.

## 6. UTILITY OF SHEARING TESTS.

In addition to the direct determination of resistance to shearing, which is of use in many instances, shearing has the advantage, as a method of testing steels, of being very simple and very economical. The preparation of plane-sided test-pieces is much less costly, and further—a consideration of great importance from the point of view of the investigation of the influence of a special element on the mechanical properties—the experiment can be repeated on the same test-piece at neighbouring points, which permits of the elimination of the influence of local defects. A tensile test gives, as a matter of fact, the fracture of the weakest

section of the test-piece, an occurrence which may arise from some cause totally independent of the chemical nature of the steel, such as cracks, flaws, or blowholes. Further, the small size of the test-pieces permits of their being taken from different localities, and so serving to establish the homogeneity or otherwise of the metal under test.

## 7. METHOD OF INVESTIGATION.

Special ternary steels containing manganese, chromium, tungsten, vanadium, molybdenum, titanium, tantalum, and boron, were made the subjects of investigation. These are the steels studied by Guillet.\*

In each class there has been shown, in a table, the designation of the steel, its chemical composition, and the results of the mechanical tests. The following abbreviations and symbols have been employed in the tables:—

$R_C$  = resistance to shear.

$E_C$  = elastic limit of shearing.

$\sigma$  = contraction on shearing (measured as described on p. 236).

$R_T$  = tensile strength.

$E_T$  = elastic limit to tensile stress.

$\Sigma$  = contraction of area to tensile stress.

$R_F$  = tensile strength deduced from the value  $R_C$  by means of Frémont's formula.

$E_F$  = tensile strength deduced from the value  $E_C$  by means of Frémont's formula.

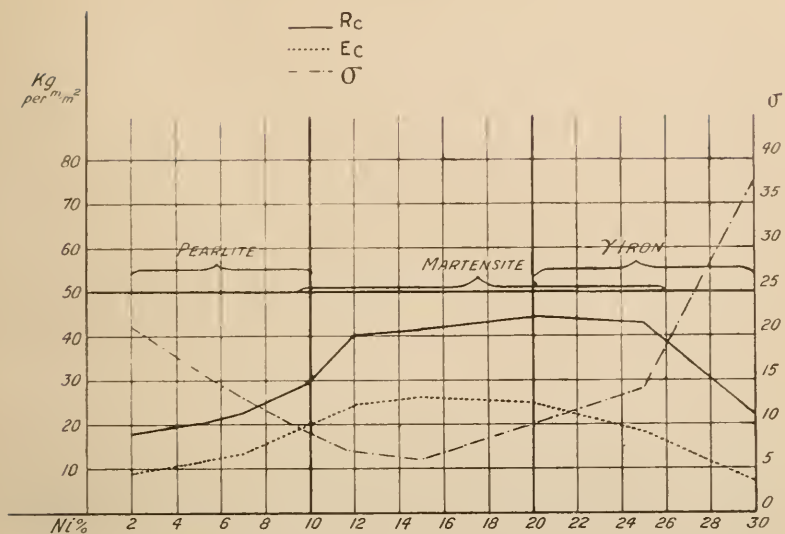
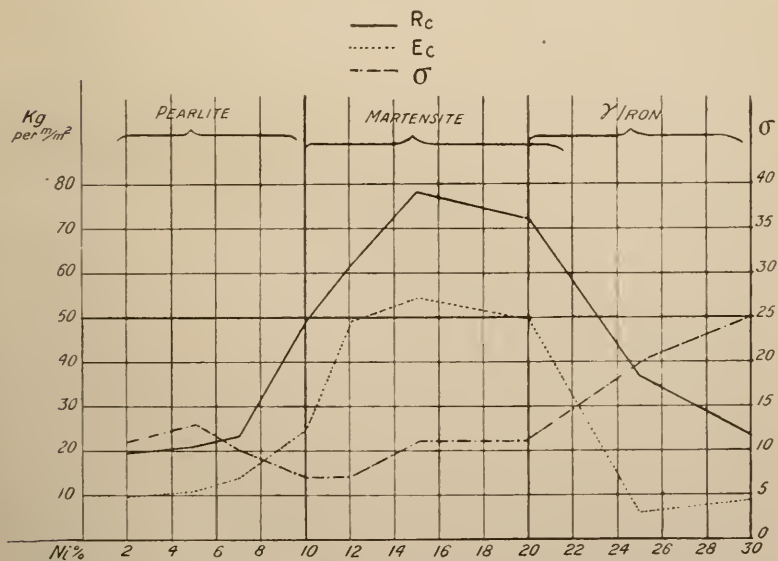
## 8. MICROSCOPIC INVESTIGATIONS.

It has been judged inexpedient to crowd this report with photomicrographs. All the test-pieces were examined under the microscope, but the author has restricted himself to indicating on the diagrams the structural areas, referring, as regards this portion of the subject, to the work of Osmond, Le Chatelier, Hadfield, and Guillet.

## NICKEL STEELS.

The experiments were carried out on three series of steels with 0.120 per cent., 0.250 per cent., and 0.800 per cent. of carbon

\* *Les Aciers spéciaux*, Paris, 1905.

FIG. 7.—Nickel Steels with 0.120 per cent. Carbon. Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .FIG. 8.—Nickel Steels with 0.250 per cent. Carbon. Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .



on an average. The analyses and the results are summed up

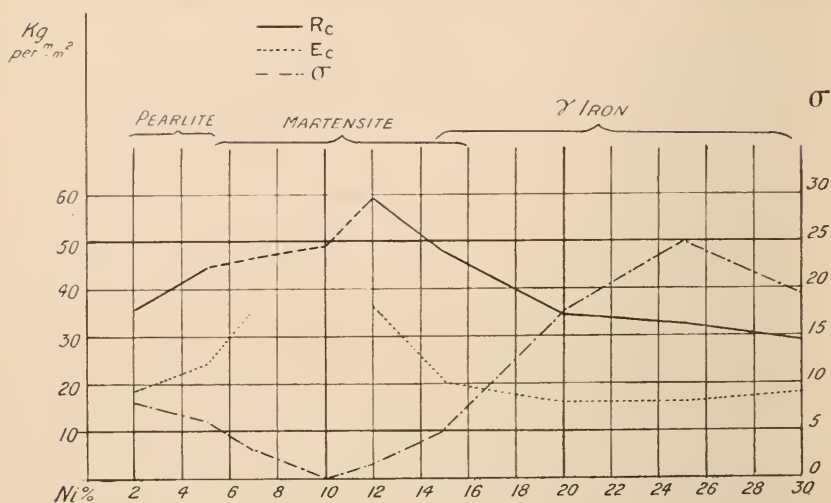


FIG. 9.—Nickel Steels with 0.800 per cent. Carbon. Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .

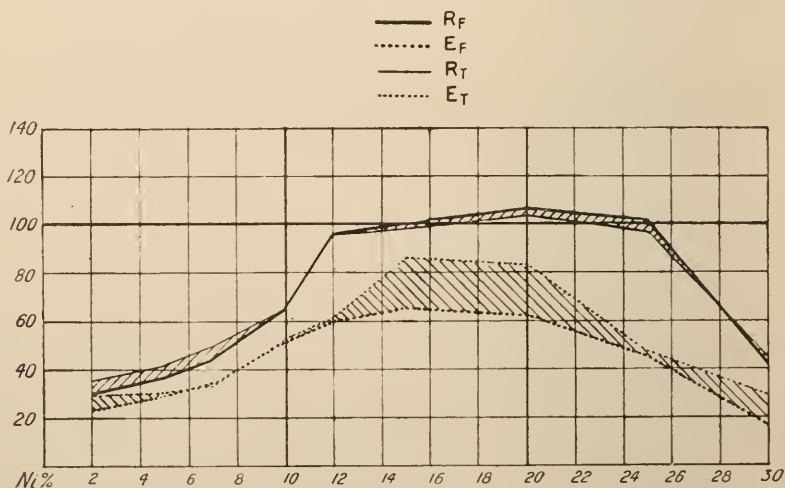


FIG. 10.—Nickel Steels with 0.120 per cent. Carbon. Comparison of Tensile and Shearing Tests. (Frémont's Formula.)

in Table I., the figures of which have served for drawing up the diagrams of Figs. 7 to 15.

TABLE I.—*Nickel Steels.*

Description.	Chemical Composition.					Shearing Tests.			Tensile Tests.			Results calculated by Brémont's Formula.
	C.	Si.	Ph.	S.	Mn.	Ni.	R <sub>c</sub> .	E <sub>c</sub> .	σ.	R <sub>t</sub> .	El.	
	Per Cent.	Per Cent.	traces	Per Cent.	Per Cent.	Per Cent.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.
<i>First Series.</i>												
1N2	0.070	0.070	traces	0.006	0.025	2.23	17.6	9	21	35.9	29.5	23
1N5	0.125	0.046	"	0.004	0.015	5.23	20	11.5	16	41	30.4	29
1N7	0.125	0.050	"	0.005	0.050	7.13	22.6	13.5	13	45	33.3	34
1N10	0.132	0.100	"	0.005	traces	10.10	29.5	20	8	63.1	52.6	51
1N12	0.125	0.090	"	0.002	"	12.07	40	24	7	96	61.6	60
1N15	0.110	0.020	"	0.004	"	15.17	41.2	26	6	97.9	86	65
1N20	0.176	0.025	"	0.004	"	20.40	44	25	10	119.7	82.7	62
1N25	0.160	0.036	"	0.007	"	25.85	42.5	18	14	97.7	47.2	45
1N30	0.120	0.031	"	traces	"	30.00	22.5	7	38	45	29.5	17
<i>Second Series.</i>												
4N2	0.206	0.030	traces	traces	0.025	1.97	19.5	9.8	11	41.8	39.5	25
4N5	0.198	0.043	"	0.003	0.025	4.90	21.5	11	13	49.8	36	27
4N7	0.225	0.081	"	traces	0.050	7.59	23.2	14	10	57.2	41.5	36
4N10	0.215	0.015	"	"	0.025	9.79	48	24.5	7	106	83	62
4N12	0.223	0.014	"	0.002	0.025	12.29	62.5	48	7	124	87.5	120
4N15	0.225	0.052	"	0.002	traces	15.04	78	54	7	114	71	135
4N20	0.220	traces	"	0.002	0.020	20.01	72	49.5	7	127.2	88.5	124
4N25	0.230	0.082	"	0.003	0.020	25.06	36.5	6	20	54.6	28.5	89
4N30	0.194	0.26	"	0.002	0.025	27.87	23.5	9	25	56	33.5	23
<i>Third Series.</i>												
9N2	0.800	0.100	traces	0.005	0.107	2.20	35.6	18.5	8	89	45.5	47
9N5	0.776	0.085	"	0.004	0.082	4.90	44.5	24	6	101	58.5	60
9N7	0.815	0.100	"	0.003	0.125	7.09	46.5	36	3	83.5	83.5	90
9N10	1.050	traces	"	0.004	0.097	9.79	49	?	0	106	106	?
9N12	0.760	0.086	"	0.004	0.082	12.27	58	36	2.5	83	83	90
9N15	0.796	0.091	"	0.007	0.060	15.04	47.5	20	5	43.5	34	50
9N20	0.800	0.089	"	0.003	0.020	20.01	34.2	16	17.5	56.5	36.5	80
9N25	0.790	traces	"	0.002	0.070	25.06	32.5	16	25	75	38	40
9N30	0.810	0.139	"	0.004	0.030	29.06	28.5	18	19.5	79.5	48.5	45

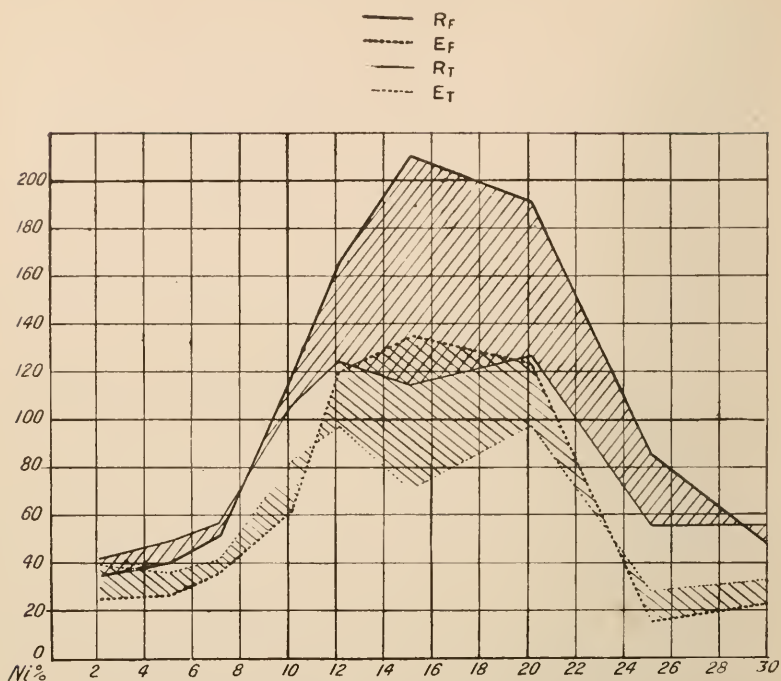


FIG. 11.—Nickel Steels with 0.250 per cent. of Carbon. Comparison of Tensile and Shearing Tests. (Frémont's formula.)

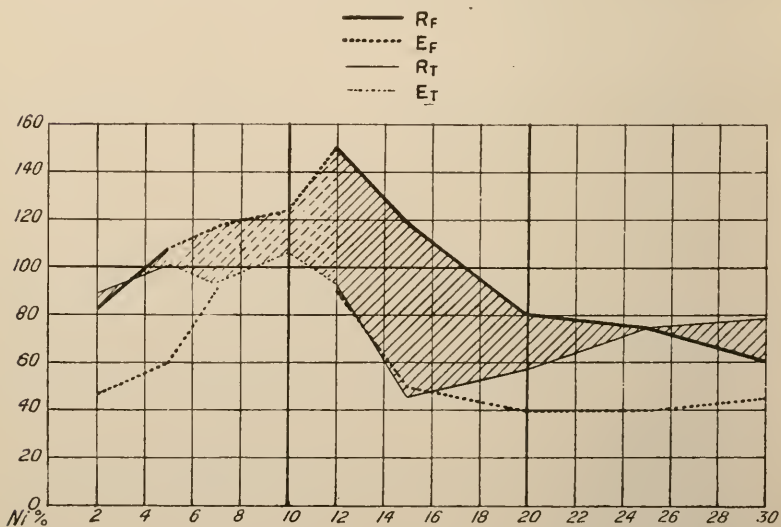


FIG. 12.—Nickel Steels with 0.800 per cent. of Carbon. Comparison of Tension and Shearing Tests. (Frémont's formula.)

# VARIATION IN THE RESULTS OF THE SHEARING TESTS IN RELATION TO THE PERCENTAGE OF NICKEL.

For the three series of steels the maximum resistance  $R_c$ , and the elastic limit of shearing,  $E_c$ , increase at first slowly,

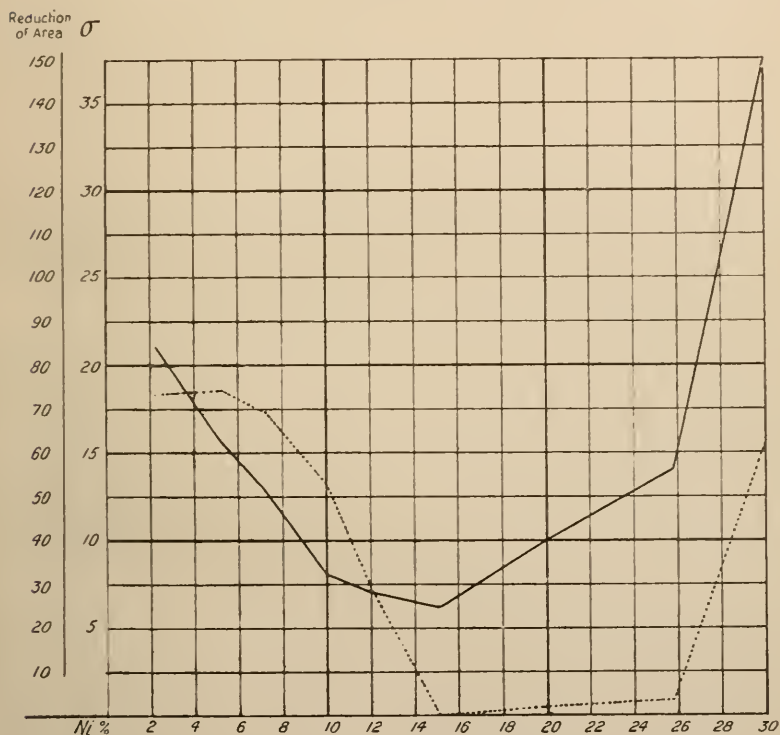


FIG. 13.—Comparison of Reduction of Area and of  $\sigma$  for Nickel Steels containing 0.120 per cent. of Carbon.

then attain, somewhat suddenly, high values, only to decrease subsequently. The shearing contraction  $\sigma$  undergoes inverse variations. The three groups met with in the tensile tests are thus again encountered.

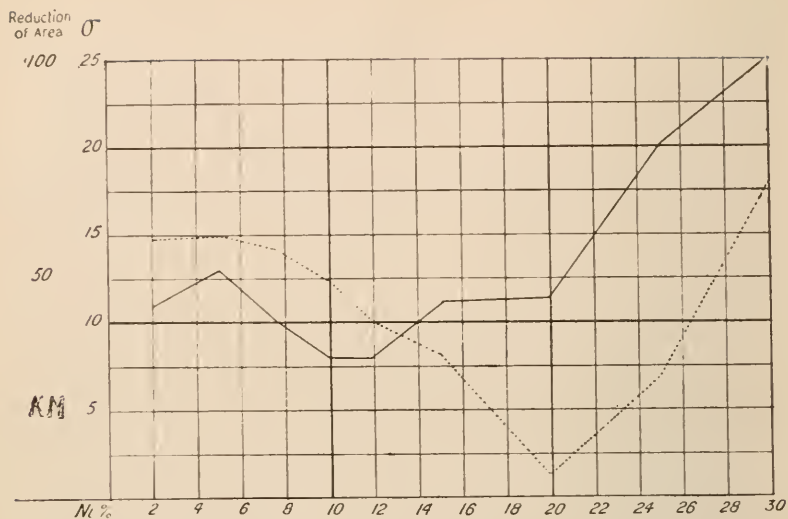


FIG. 14.—Comparison of Reduction of Area and of  $\sigma$  for Nickel Steels containing 0.250 per cent. of Carbon.

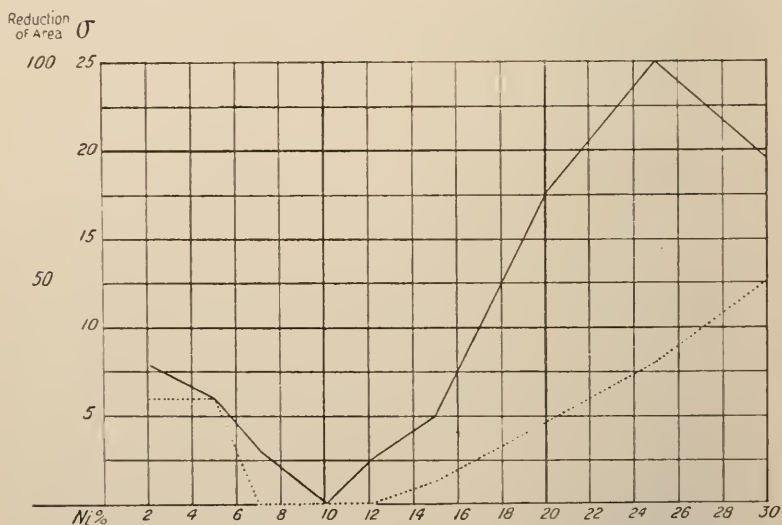


FIG. 15.—Comparison of Reduction of Area and of  $\sigma$  for Nickel Steels containing 0.800 per cent. of Carbon.

*First Group.*— $R_c$ ,  $E_c$ , and  $\sigma$ , in the neighbourhood of the carbon steels, for—

Nickel per Cent.	Carbon per Cent.
< 10	0.120
< 7	0.250
< 5	0.800

It should be remarked that for these steels the difference,  $R_c - E_c$ , is very nearly constant in each series and equal, on an average, to—

K5.	Carbon per Cent.
8 for steels . . . . .	0.120
10 „ . . . . .	0.250
18 „ . . . . .	0.800

*Second Group.*— $R_c$  and  $E_c$  very high and  $\sigma$  very low; the difference between  $R_c$  and  $E_c$  being greater in proportion as  $R_c$  is higher.

This group corresponds, for all three series, to percentages of nickel comprised, respectively, within the following limits: 10 to 26 per cent.; 7 to 24 per cent.; and 5 to 15 per cent.

*Third Group.*— $R_c$  and  $E_c$  have medium values comparable with those of the first group, but with a greater difference, nevertheless, between the two quantities.  $\sigma$ , however, attains very high values, which increase rapidly with the increase in the percentage of nickel.

#### RELATIONS TO THE MICROSTRUCTURE.

These three groups obviously correspond with the three structures formerly met with in the nickel steels—

First group: pearlitic steels.

Second group: martensitic steels.

Third group: polyhedral steels.

These three divisions are indicated in the diagrams; they slightly overlap one another in the parts corresponding to the zones of transformation, in which the structure partakes simultaneously of the nature of the two neighbouring groups.



It is to be noticed that the angle which the lines of the diagram make with the horizontal, which corresponds with the period of regularly incremental increases in elongation, varies within considerable proportions, and it would appear,

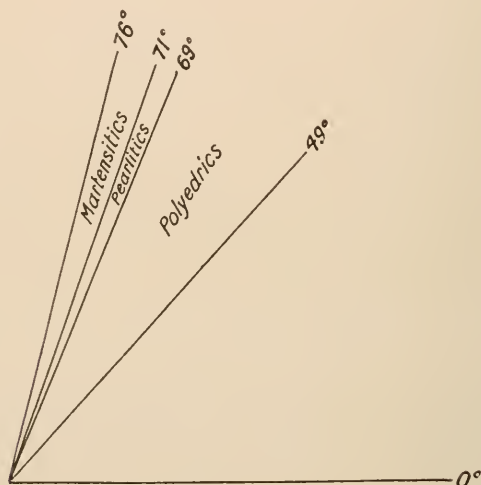


FIG. 16.

as is shown in Fig. 16, that this angle depends upon the constitution of the steel experimented upon.

#### COMPARISON OF THE RESULTS OF THE TENSILE AND SHEARING TESTS.

1. *Maximum Strength and Elastic Limit.*—As is shown in the diagrams, these factors vary in the same proportion in Figs. 10 to 12, in which the results of the tensile tests have been compared with the figures found by employing the Frémont formula. If a certain amount of concordance exists between them when  $30 \text{ kilogrammes} < R_T < 100$ , it is no longer so, for  $R_T > 100$ . The differences become immense, and the formulæ are consequently inapplicable.

By eliminating the figures that appear to be slightly

abnormal, it has been possible to combine  $R_T$  and  $R_C$  by the two following linear formulæ :—

For pearlitic or polyhedral steels—

$$R_T = 2.6R_C - 11.5, \text{ and}$$

For the martensitic steels—

$$R_T = 42.5 + 1.3R_C.$$

It is plain that these ratios require to be checked by a much larger number of tests, but they at least show the impossibility of combining  $R_T$  and  $R_C$  by means of a single linear formula.

Perhaps it might be feasible to secure more satisfactory results by employing equated expressions of a higher order—*e.g.* by those of a parabola circumscribing the two right lines shown by the above formulæ.

2. *Contraction of Area.*—Figs. 13, 14, and 15, in which have been compared the variations of  $\sigma$  and  $\Sigma$ , reveal curves which, from their appearances, have evidently a close relation to each other, but no way has been found of combining with them, in any one law, the modifications undergone by these factors owing to the introduction, in the steel, of increasing increments of nickel.

It is needful to remark the sensitiveness of the factor  $\sigma$ , which can further supply an excellent means of checking the quantity of nickel in the steel. For the martensitic steel the values are, as a matter of fact, practically *nil*, whereas very high figures are obtained for the polyhedral steels, and, in the case of these latter steels, it is very easy to stop the operation once the maximum tensile stress has been reached, instead of proceeding to the complete rupture of the test-piece—a mode of procedure which is almost impossible with the martensitic steels.

#### VARIATION IN STRUCTURE CONSEQUENT ON SHEARING.

Turning to account this property of the polyhedral steels, it became possible, by polishing the samples not completely sheared, to observe the deformations produced in the zone of

contraction by the influence of shearing. In most of the cases there was observed a considerable elongation of the polyhedrons, but in the case of a steel with 0·8 per cent. of carbon and 15 per cent. of nickel, there was found a modification in

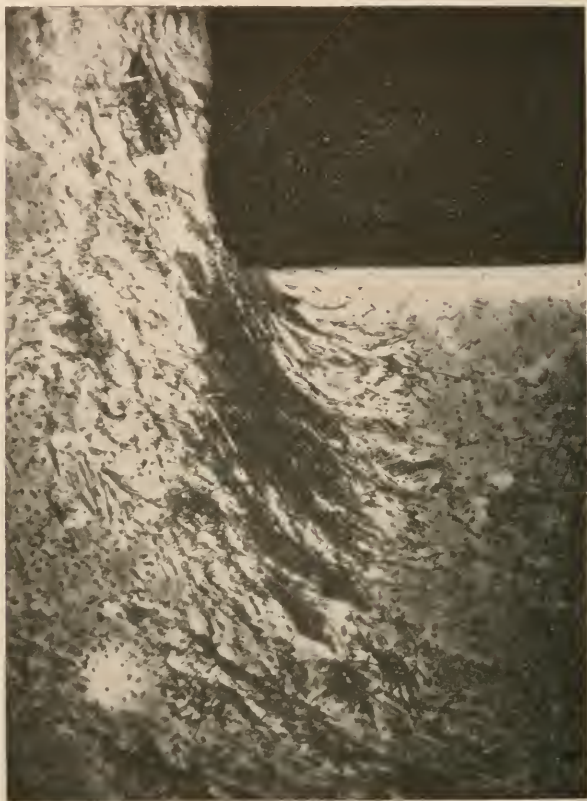


FIG. 17.

the actual nature of the constituents by the appearance, in the midst of the polyhedrons, of troosto-sorbite. This result, which should be regarded as a phenomenon of strain, corresponds with a modification in the state of physico-chemical equilibrium at the ordinary temperature, consequent on a very great variation in the initial equilibrium factor.

TABLE II.—*Manganese Steels.*

Description.	Chemical Composition.					Shearing Test.			Tensile Test.			Results calculated by Fremont's Formula.	
	C.	Si.	S.	Ph.	Mn.	R <sub>C</sub> .	E <sub>C</sub> .	σ.	R <sub>T</sub> .	E <sub>T</sub> .	Σ.	R <sub>T</sub> .	E <sub>T</sub> .
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.
8M0.5	0.873	1.351	0.020	0.024	0.461	43	29.7	7.5	111.9	59.5	9	102	75
8M1	0.840	0.573	0.024	0.015	1.031	45.3	31	5	118.3	68.5	9	108	85
8M2	0.930	1.028	0.018	0.011	1.972	46	30.9	8	105.4	79.1	3	110	77
8M3	0.934	1.446	0.015	0.010	3.084	48.5	33.4	5	100.9	82.8	0	117	83
8M5	0.762	1.118	0.013	0.011	5.112	60.8	46	3	86.6	60.2	3	152	115
8M7	0.700	0.745	0.010	0.021	7.200	49	14.2	23	56.5	41.4	7.5	119	35
8M10	0.922	0.721	0.013	0.016	10.080	49	13.8	25.5	97.8	48.2	14.7	119	35
8M12	0.960	0.876	0.011	0.013	12.006	48.2	15.6	21.2	89.6	61.8	14.7	116	39

It would, in this connection, be difficult to decide whether, for the steel under consideration, the polyhedral structure corresponds with the stable condition at the ordinary temperature, or with a condition of unstable equilibrium. The cooling of martensitic steels, even when conducted very slowly, leaves them in this state, which is manifestly one of unstable equilibrium, martensite being a transition constituent, and, in the case where the transformation-point is in the near neighbourhood of the ordinary temperature, the steel may retain its polyhedral structure. This state, which is thus unstable, may favour the action of the pressure, but it is not at all essential; and pressure itself, being one of the factors of equilibrium, may produce a structural alteration in a steel which has attained, at the ordinary temperature, the condition of stable equilibrium.

### MANGANESE STEELS.

The steels investigated contained, on an average, 0·8 per cent. of carbon, the proportions of manganese rising from 0·5 to 12 per cent. Table II. summarises the chemical analyses and the mechanical tests which have been plotted as curves in Figs. 18 and 19.

#### VARIATION IN THE RESULTS OF THE SHEARING TESTS IN RELATION TO THE PERCENTAGE OF MANGANESE.

Fig. 18 shows very clearly that these steels may be ranged into two classes, according to the results of the shearing tests.

*First Class.*—When the percentage of manganese increases from 0·5 to 5 per cent. the resistance to shear  $R_c$ , and the elastic limit,  $E_c$ , increase until they have attained very high values ( $R_c = 61$  kilogrammes,  $E_c = 46$  kilogrammes), whereas  $\sigma$  diminishes slightly.

*Second Class.*—Steels containing more than 5 per cent. of manganese. Resistance to shear,  $R_c$ , remains constant, in the neighbourhood of 50 kilogrammes; the elastic limit is low

(it remains between 10 kilogrammes and 20 kilogrammes), while  $\sigma$  reaches high values ranging from 20 to 30.

#### RELATIONS TO THE MICROSTRUCTURE.

Microscopic examination permits very clearly of the differentiation of the two classes just indicated. The first class

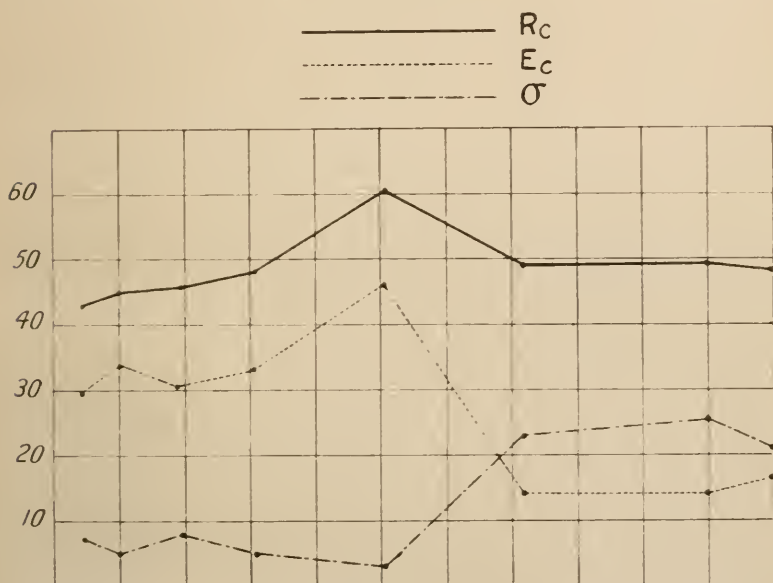


FIG. 18.—Manganese Steels containing 0.8 per cent. of Carbon.  
Variations of  $R_c$ ,  $E_c$ ,  $\sigma$ .

corresponds with pearlitic steels and troostite, and the second with  $\gamma$ -steels.

It may also be remarked that as long as the steels are simply pearlitic—that is to say, up to 3 per cent.—the increase of  $R_c$  and  $E_c$  is inconsiderable, but that they subsequently attain very high values with 5 per cent. of manganese. It will be seen that this differentiation is even more clearly defined by a comparison of the tensile and shearing tests.



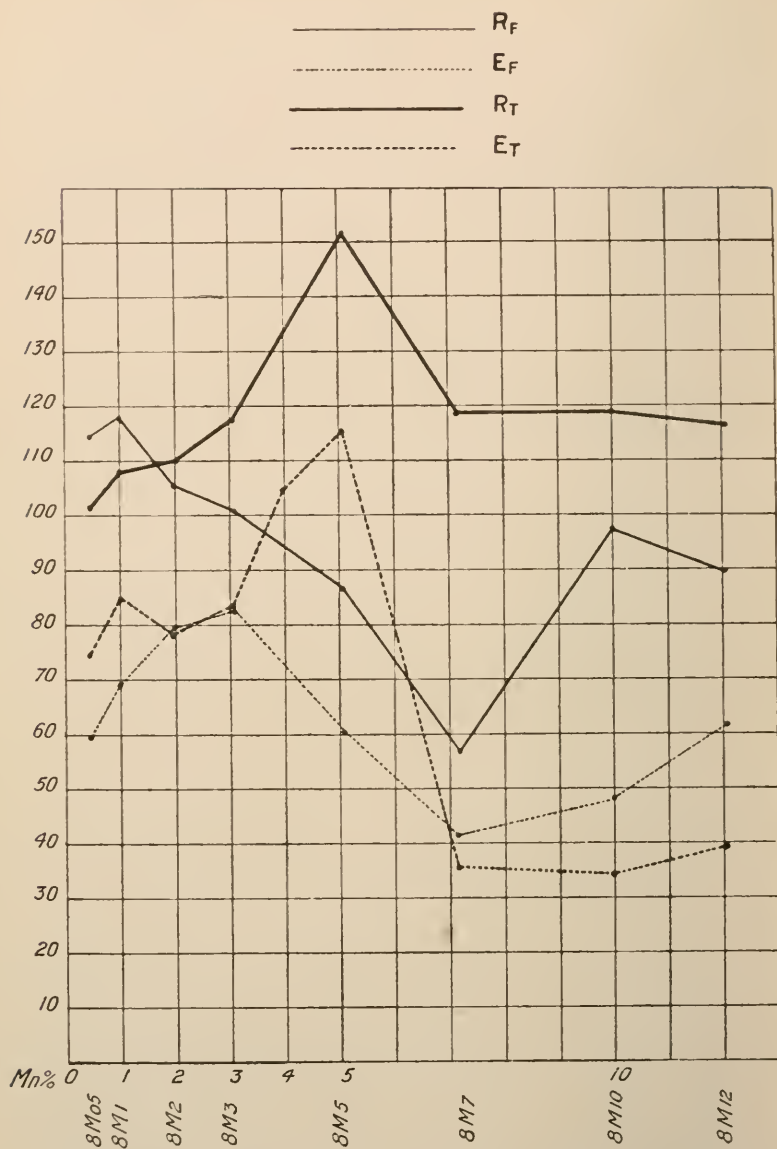


FIG. 19.—Manganese Steels containing 0.800 per cent. of Carbon. Comparison of Tensile and Shearing Tests. (Fremont's formula.)

## COMPARISON OF THE RESULTS OF THE TENSILE AND SHEARING TESTS.

Fig. 19 shows the remarkable disagreement between the results obtained experimentally by the tensile tests and those calculated by means of the Frémont formulæ. The divergence is particularly important as regards steels containing from 3 to 7 per cent. of manganese—that is to say, for the martensitic and troostitic steels. With steel 8M5 the difference between  $R_F$  and  $R_T$  attains 76 kilogrammes, and the difference between  $E_F$  and  $E_C$  is 61 kilogrammes; the calculated figures are nearly double the figures actually obtained. It must be concluded that these steels offer an exceptional degree of resistance to shearing.

On the other hand, the divergence between the figures calculated and those actually obtained becomes smaller for the pearlitic steels and for those containing  $\gamma$ -iron.

## CHROMIUM STEELS.

Three series of chromium steels were studied, one low in carbon and containing on an average 0.2 per cent., and the others containing about 0.8 per cent. of carbon. The results of the chemical analysis and of the mechanical tests are shown in Table III., and the curves given in Figs. 20 to 23 have been plotted from the numbers given in this table.

## VARIATION IN THE RESULTS OF THE SHEARING TESTS IN RELATION TO THE PERCENTAGE OF CHROMIUM.

1. *Steels containing 0.2 per Cent. of Carbon.*—If the curves shown in Fig. 20 be examined, three areas can be distinguished—

(a) The resistance to shearing increases with the percentage of chromium, but remains below 50 kilogrammes. It is to be regretted that there did not remain enough of the steel 1C5 to complete the shearing test, as the limits of this group cannot be clearly defined in consequence.

TABLE III.—*Chromium Steels.*

Description.	Chemical Composition.					Shearing Test.			Tensile Test.			Results calculated by Frémont's Formula.		
	C.	Si.	S.	Ph.	Mn.	Cr.	Rc.	E <sub>c</sub> .	σ.	R <sub>t</sub> .	E <sub>t</sub> .	Σ.	R <sub>e</sub> .	E <sub>p</sub> .
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.
<i>First Series.</i>														
1C0.5	0.043	0.971	traces	0.015	traces	0.70	...	...	...	35.4	22.6	74.9	...	...
1C1	0.058	0.700	"	0.016	"	1.20	19	9	22	56.5	42.9	58.2	...	33
1C2	0.223	0.050	"	0.015	0.210	2.71	35.8	21	11.5	...	...	...	...	81
1C3	0.280	0.050	"	0.010	0.150	2.66	37.1	22	12.5	...	...	...	...	84
1C5	0.214	0.232	0.008	0.020	traces	4.50	...	...	...	60.3	56.5	62.1	...	...
1C7	0.071	0.120	0.014	0.010	"	7.84	51.5	34	14.5	150.6	99.7	7.5	...	126
1C9	0.014	0.338	0.004	0.015	"	9.14	...	...	...	143.1	129.6	4.5	...	...
1C10	0.154	0.200	0.028	0.006	"	10.14	68	52	6.5	139.3	101.7	0	...	173
1C11	0.154	0.350	traces	0.010	0.180	10.77	66	48	6	...	...	...	...	167
1C12	0.142	0.210	0.015	0.016	traces	13.60	...	...	...	86.8	50.4	7.5	...	...
1C13	0.166	0.270	traces	0.015	"	13.65	33	27	12.3	...	...	...	...	73
1C15	0.382	0.469	0.011	0.013	"	14.52	32.3	24	10	100.1	89.3	7.2	...	71
1C20	0.210	0.527	traces	0.011	"	22.06	...	...	...	65.7	...	24.5	...	...
1C25	0.244	0.256	0.013	0.020	0.108	25.31	32.3	16	20	57.3	40.1	52.5	...	70
1C30	0.464	0.373	0.006	0.024	traces	31.75	32	17	20	57.5	43.3	50.4	...	70

*Second Series.*

8C0.5	0.865	0.243	0.017	0.015	0.027	0.62	49	34	8	109.2	79.1	16.6	...	119	85
8C1	0.973	0.221	0.016	0.013	0.244	0.99	57	35	3	131.8	131.8	7.5	...	142	88
8C2	0.887	0.280	0.033	0.020	0.108	2.14	56	37	6	139.2	97.9	0	...	139	93
8C5	0.789	0.420	0.023	0.016	traces	4.57	56	34.5	6.2	133.3	84.4	7.5	...	138	86
8C7	0.840	0.409	0.031	0.018	0.056	7.28	40	24.5	11	124.3	60.2	17.6	...	93	61
8C10	0.751	0.885	0.005	0.024	traces	9.38	39.5	22.5	12	94.1	79.1	0	...	91	56
8C12	0.961	0.409	0.047	0.013	0.056	11.52	39.5	20	11.5	132.5	79.1	14.7	...	91	50
8C15	0.741	0.486	0.038	0.008	traces	14.54	39.5	24.5	10.8	120	65.5	0	...	91	61
8C16	0.705	0.180	traces	0.010	0.240	13.94	37	23.5	9	...	...	...	...	85	57
8C20	0.905	0.745	0.007	0.010	traces	18.65	44	31	8	128	128.5	0	...	104	77
8C25	0.820	0.584	0.008	0.016	"	26.54	31	14	18.5	59.3	48.9	45.1	...	68	36
8C30	0.916	0.469	0.012	0.021	"	32.46	...	...	...	67.8	56.4	40.8	...	...	...
8C35	0.828	0.326	0.014	0.026	"	36.34	42	26	20	...	...	...	...	99	64

(b) Steels with a very high resistance to shearing, reaching 65 to 75 kilogrammes; on the other hand,  $\sigma$  is low. They contain 7 to 13 per cent. of chromium.

(c) Steels whose resistance to shearing remains within 30 to 35 kilogrammes, but in which  $\sigma$  increases with the per-

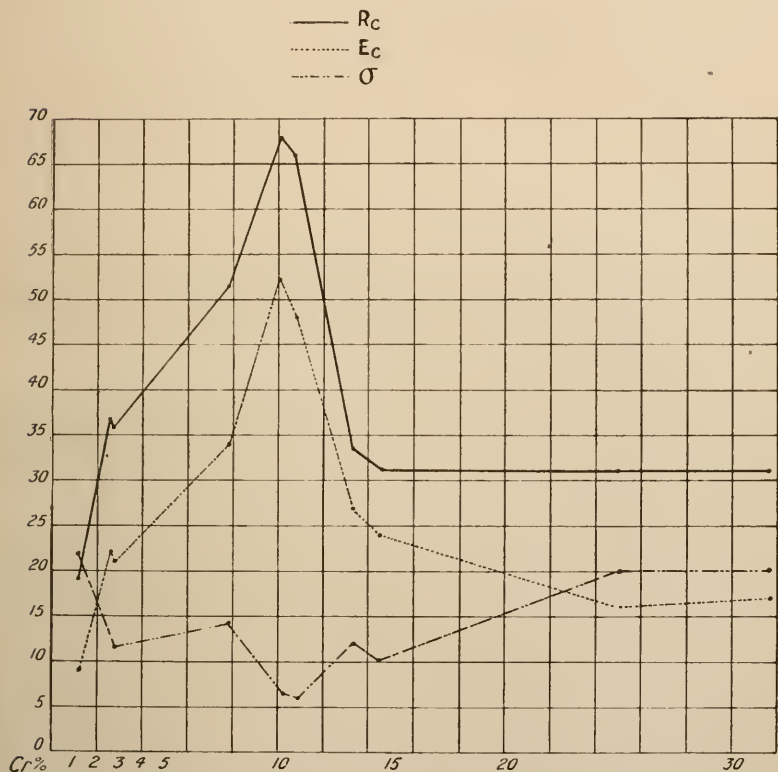


FIG. 20.—Chromium Steels containing 0.2 per cent. of Carbon.  
Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .

centage of chromium, whereas  $E_c$  decreases. These steels contain more than 13 per cent. of chromium.

The value of  $E_c$  follows the variations in that of  $R_c$ , and even up to 7 per cent. of chromium the typical curves are practically parallel.

2. *Steels containing 0.8 per Cent. of Carbon* (Fig. 21).—The results range these steels into three groups—

(a) Steels with a high resistance to shearing (over 45 kilogrammes) which contain up to 5 per cent. of chromium. The elastic limit of shearing is high, but  $\sigma$  is low.

(b) Steels exhibiting remarkable regularity in their resistance to shearing (from 37 to 40 kilogrammes) despite the increasing percentages of chromium.  $E_c$  remains between

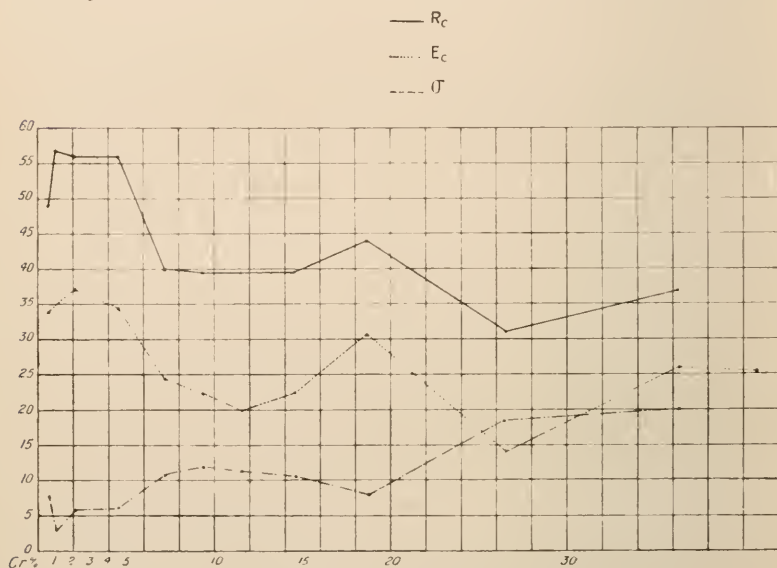


FIG. 21.—Chromium Steels containing 0.8 per cent. of Carbon.  
Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .

0 and 25 kilogrammes, and  $\sigma$  between 10 and 12. The mechanical properties on shearing remain, therefore, practically unaltered. These steels contain 7 to 14 per cent. of chromium.

(c) Steels containing more than 18 per cent. of chromium, the percentage of chromium gradually increasing. The resistance and elastic limit on shearing diminish, if anything, but what is chiefly characteristic of these steels is the increase in  $\sigma$ , which reaches as high as 20.

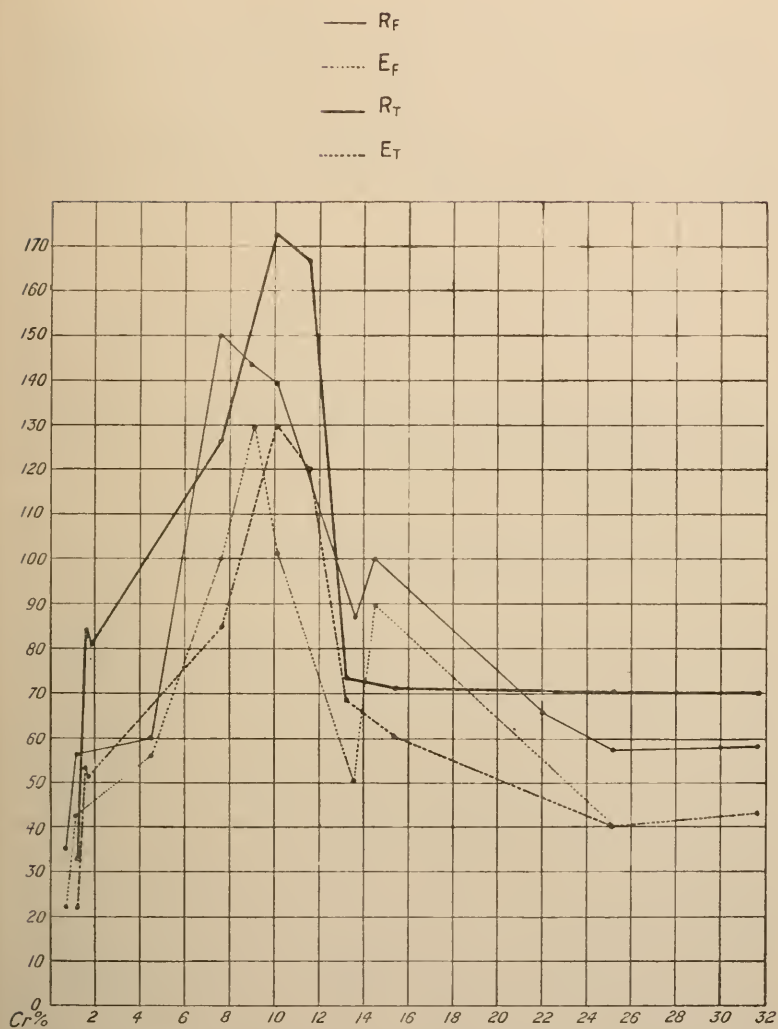


FIG. 22.—Chromium Steels containing 0.200 per cent. of Carbon. Comparison of Tensile and Shearing Tests. (Frémont's formula.)



## RELATION TO MICROSTRUCTURE.

Microscopic examination again re-establishes the existence of the three classes in each series. The micrographic study of these steels having already been published in detail, the author will, in this place, confine himself to recalling the fact that these three groups may be distinguished by the nature of the predominating constituent—

First group: pearlitic steels.

Second group: martensitic steels.

Third group: steels containing the double carbide.

No alteration whatever was noticeable, as regards the constituents of these steels, apart from the mechanical deformations within the zone of fracture.

COMPARISON OF THE RESULTS OF THE TENSILE AND  
SHEARING TESTS.

Figs. 22 and 23 show, in the form of curves, this comparison. Considerable difference will be noticed between the results obtained with the tensile tests and those calculated by means of Frémont's formula. The divergence is at its minimum in the case of the pearlitic steels, and at its maximum in that of the martensitic steels; with the latter it reaches as much as 40 kilogrammes per square millimetre. It would even appear that this was not a matter of the absolute value of the figures, for, in the case of steels containing the double carbide, for which the constants of tensile strength are not very much higher than those containing ordinary proportions of carbon, a fairly considerable difference may be remarked. There is, however, a similarity of form in the appearance of the curves for the steels with 0·2 per cent. of carbon, but this fact disappears when the steels containing 0·8 per cent. of carbon are taken into consideration.

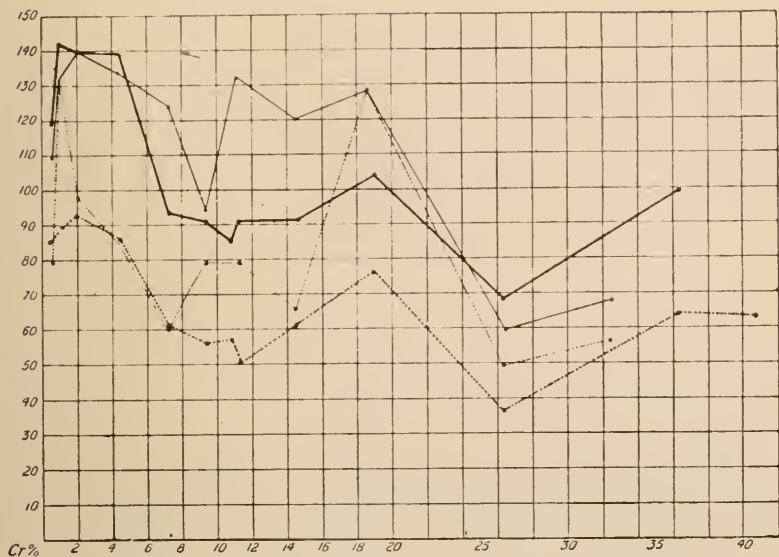


FIG. 23.—Chromium Steels containing 0.800 per cent. of Carbon. Comparison of Tensile and Shearing Tests. (Frémont's formula.)

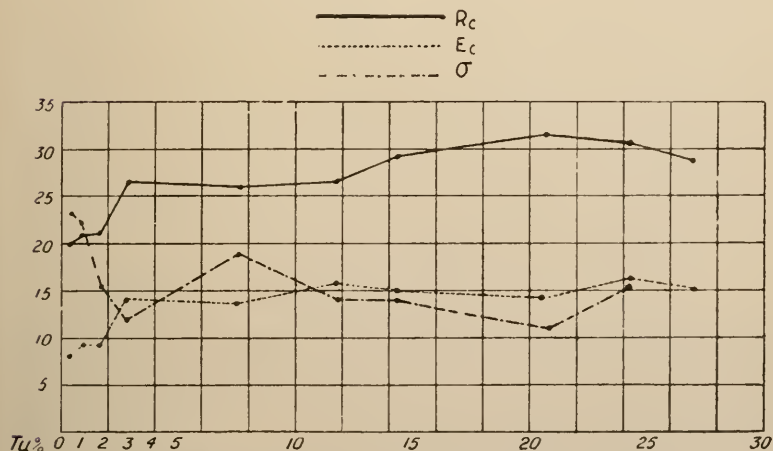


FIG. 24.—Tungsten Steels containing 0.2 per cent. of Carbon. Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .

## TUNGSTEN STEELS.

Two series of tungsten steels have been experimented with, one with percentages of carbon comprised within 0.11 and 0.27 per cent. and containing from 0.4 to 27 per cent. of tungsten, and the other containing at least 0.8 per cent. of

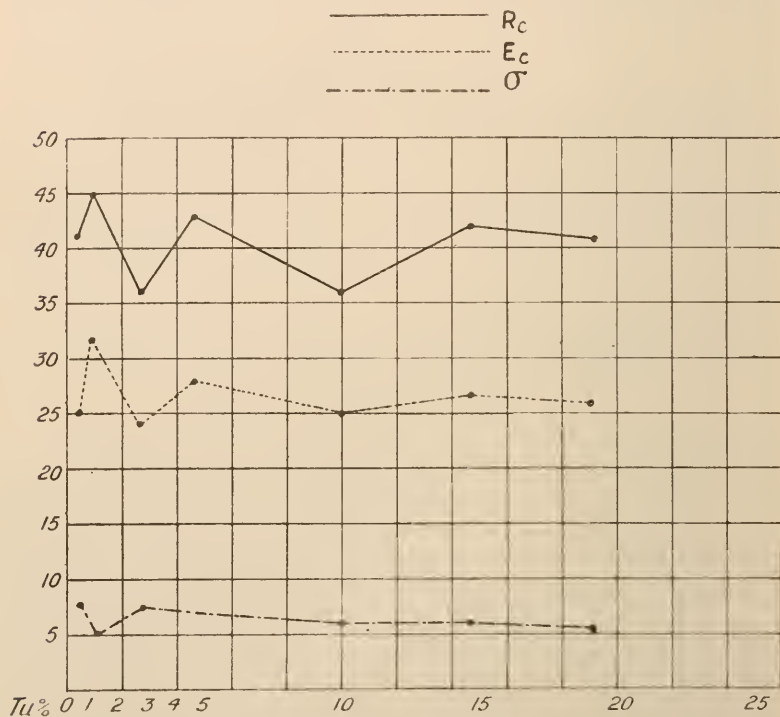


FIG. 25.—Tungsten Steels containing 0.8 per cent. of Carbon.  
Variations of  $R$ ,  $E_c$ , and  $\sigma$ .

carbon and up to 19 per cent. of tungsten. The results obtained, which are grouped in Table IV. and co-ordinated in Figs. 24 to 27, are very irregular, and do not admit of any conclusions being drawn from them—

1. For the steels containing not less than 0.2 per cent. the tensile strength and the elastic limit in shearing increase

TABLE IV.—*Tungsten Steels.*

Description.	Chemical Composition.						Shearing Test.			Tensile Test.				Results calculated by Frémont's Formula.	
	C.	Si.	S.	Ph.	Mn.	Tu.	Re.	Ec.	σ.	Rt.	El.	N.	R <sub>F</sub> .	Kilos.	
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	
1T0.5	0.117	0.035	traces	0.013	traces	0.41	20.4	8	23.2	41.1	31.1	66.5	41	20	
1T1	0.110	0.038	0.005	0.016	"	0.93	20.8	9.2	22.5	42.1	31.6	63.9	38	23	
1T2	0.110	0.036	0.008	0.010	"	1.75	21.1	9.2	15.5	48.9	37.6	62.1	29	23	
1T5	0.128	0.035	traces	0.015	"	4.96	26.7	14	12	63.2	33.9	63.0	55	35	
1T7	0.130	0.030	"	0.010	"	6.90	26.4	13.6	19	"	"	"	54	34	
1T10	0.173	0.046	0.013	0.008	0.067	11.89	26.7	16	14	86.6	79.1	47.7	55	40	
1T15	0.201	0.060	0.008	0.013	traces	14.37	29.2	15	14	77.2	54.6	14.7	62	38	
1T20	0.221	0.139	0.013	0.011	"	20.71	31.6	14.4	11	71.5	48.9	26.4	69	39	
1T25	0.219	0.112	0.014	0.013	"	24.35	30.6	16.4	15.5	60.2	41.4	7.5	66	41	
1T30	0.276	0.139	0.012	0.016	"	27.05	27.8	15.2	14.5	67	56.4	0	60	38	
8T0.5	0.861	0.040	0.033	0.012	0.027	0.40	41	25	8	103.2	56.4	17.6	95	63	
8T1	0.658	0.120	0.023	0.015	0.054	0.95	45	32	5	113	62.8	7.5	107	80	
8T2	0.794	0.058	0.019	0.010	0.054	2.75	36	24	7.5	124.3	75.3	17.6	82	60	
8T5	0.328	0.140	0.018	0.008	traces	4.68	43	28	7	126.5	85.8	16.3	108	69	
8T10	0.815	0.093	0.014	0.015	"	9.99	36	25	6	134.8	101.7	3	82	63	
8T15	0.712	0.117	0.023	0.015	"	14.75	42.1	26.8	6	129.9	67.8	3	99	67	
8T20	0.737	0.066	0.018	0.070	"	19.25	41	26	5.5	105.4	71.5	4.5	94	65	

regularly up to 20 per cent. of tungsten, to diminish slightly after. It may be seen that there is no relation whatever to the microstructure, and the most that can be observed is that the proportion of 10 per cent. of tungsten which corresponds with the appearance of the double carbide also marks the

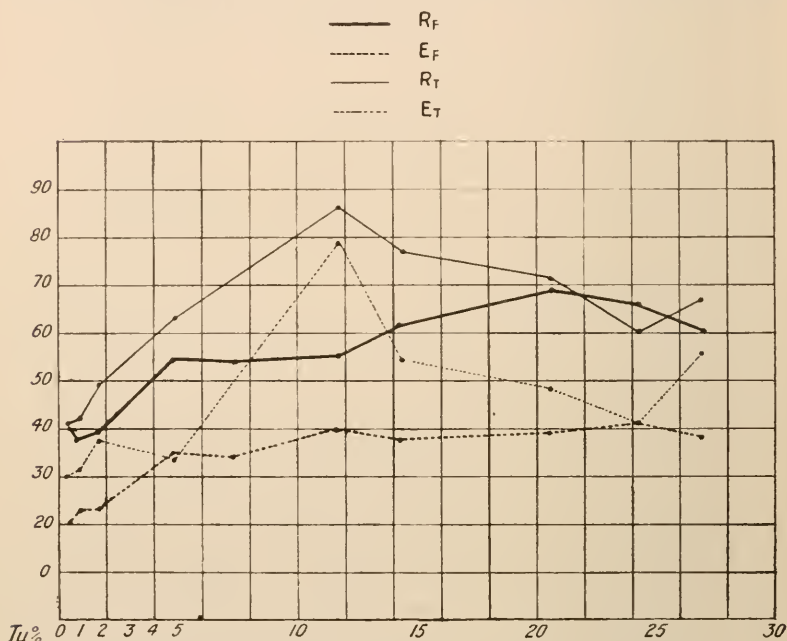


FIG. 26.—Tungsten Steels containing 0.2 per cent. of Carbon. Comparison of Tensile and Shearing Tests. (Frémont's formula.)

limit where the constant of divergence,  $R_c - E_c$ , which can be seen in the low percentages of tungsten, ceases.

It is impossible thus to find any agreement between the curve representing the tensile tests and those corresponding with the shearing tests, while the latter are expressed by a difference between the figures for the tensile tests and those calculated by the Frémont formulæ, which is at its maximum with the steel containing 10 per cent. of tungsten.

2. *Steels with 0.8 per cent. of Carbon.*—The results of the shearing tests are exceedingly irregular; zig-zag curves (Figs. 25 and 27) are obtained, which are comprised between the

ordinates 35 and 45 kilogrammes for R, and 23 and 35 kilogrammes for E. There can, therefore, be no question of seeking a relation with the structure or of establishing comparisons with the tensile tests, besides which, as regards the

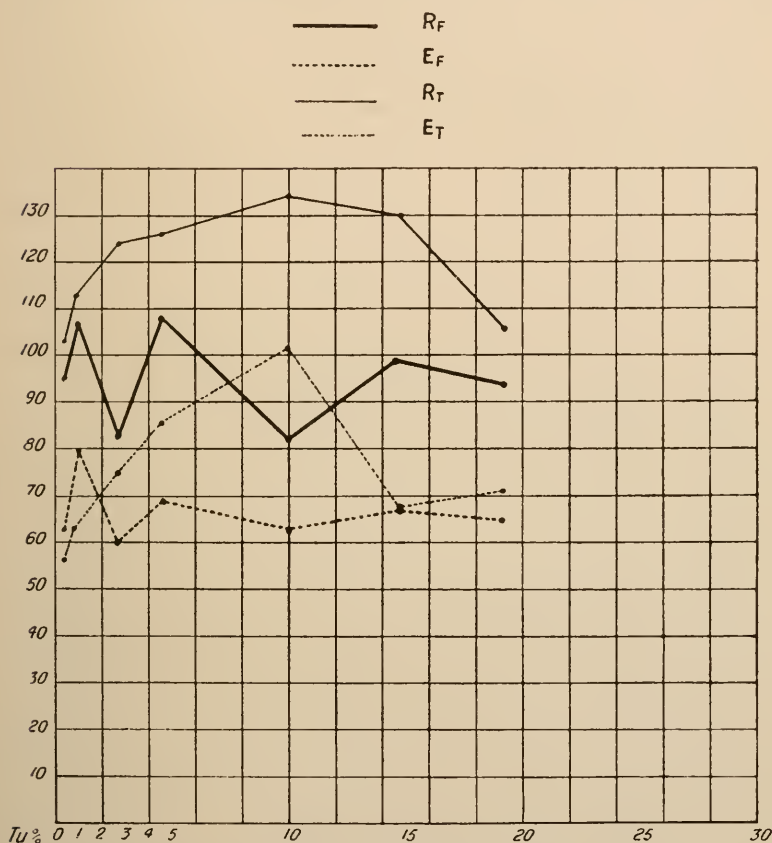


FIG. 27.—Tungsten Steels containing 0.8 per cent. of Carbon. Comparison of Tensile and Shearing Tests. (Frémont's formula.)

latter point, Fig. 27 shows sufficiently well what a considerable divergence there is between the results of the tensile tests and the figures calculated from Frémont's formulæ. For the steels containing 1 per cent. of tungsten there is, at most, but a slight agreement in the results.



## ALUMINIUM STEELS.

Eleven aluminium steels were investigated, of which four had a low carbon content, and seven contained from 0.65

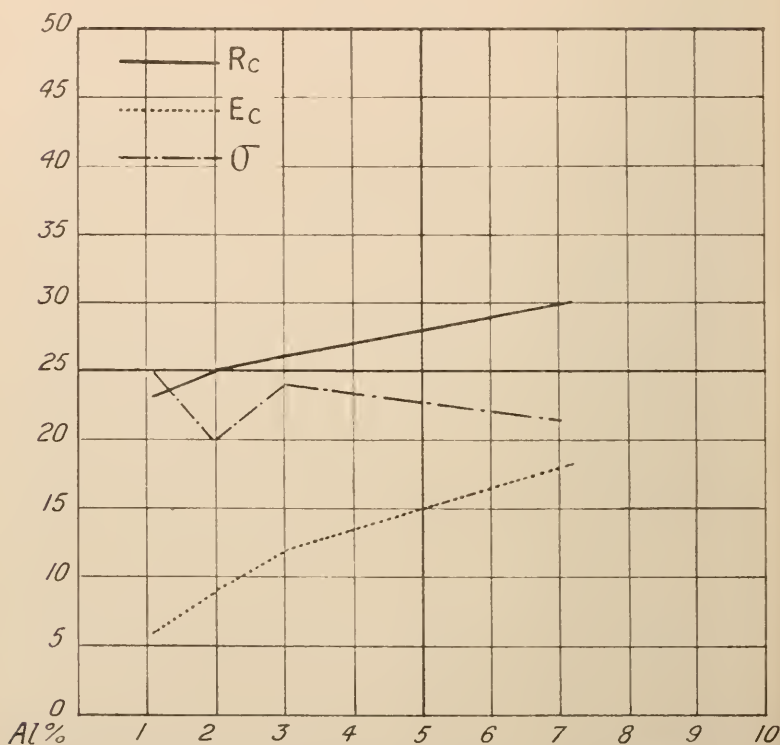


FIG. 28.—Aluminium Steels containing 0.200 per cent. of Carbon.  
Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .

to 0.85 per cent. of carbon and up to 15 per cent. of aluminium. Table V. gives, together with the chemical analyses, the results of the shearing and tensile tests, by means of which the curves shown in Figs. 28 to 31 were plotted.

TABLE V.—*Aluminium Steels.*

Description.	Chemical Composition.						Shearing Test.			Tensile Test.			Results calculated by Frenont's Formula.	
	C.	Si.	S.	Ph.	Mn.	Al.	R <sub>u</sub> .	E <sub>u</sub> .	σ.	R <sub>t</sub> .	E <sub>t</sub> .	Σ.		
	Per Cent. 0·113	Per Cent. 0·070	Per Cent. 0·014	Per Cent. 0·029	Per Cent. traces	Per Cent. 1·99	Kilos. 23	Kilos. 7	Kilos. 25·5	Kilos. 40·8	Kilos. 33·6	Kilos. 63·2	Kilos. 44	Kilos. 17
1A1	0·168	traces	0·022	0·008	„	2·04	25	9	20·2	44·5	27·9	66·7	49	23
1A2	0·134	0·105	0·013	0·016	„	3·05	26	12	24·5	41·1	27·4	32·9	51	30
1A7	0·083	0·117	0·017	0·020	0·057	7·18	30	18	23	46·1	40·9	0	65	41
8A0·5	0·736	0·140	0·008	0·015	0·100	0·45	40	21	11	83·3	45·8	17·3	91	52
8A1	0·669	0·198	0·012	0·008	0·140	1·05	41	21·5	10·1	88·8	46·6	20·5	95	54
8A3	0·691	0·186	0·018	0·006	0·152	2·89	39	22	8	73·8	43·6	4·5	91	55
8A5	0·815	0·221	0·024	0·024	0·122	4·65	46	28	6·5	88·8	46·7	15·4	109	70
8A7	0·663	0·256	0·025	0·050	0·140	7·00	38	26	7·4	89·4	68·4	0	88	73
8A10	0·666	0·116	0·024	0·034	0·091	9·45	...	29	?	73·0	68·4	0	?	73
8A15	0·860	0·232	0·018	0·032	0·398	14·90	46	30	5	101·9	66·2	4·2	110	74

### VARIATION IN THE RESULTS OF THE SHEARING TESTS IN RELATION TO THE PERCENTAGE OF ALUMINIUM.

1. *Steels containing 0.2 per Cent. of Carbon* (Fig. 28).—Resistance to shear increases fairly regularly with the percentage of aluminium, and rises from 23 to 30 kilogrammes when the percentage of aluminium rises from 1 to 7 per cent. The elastic limit rises, under the same conditions, from 7 to 18 kilo-

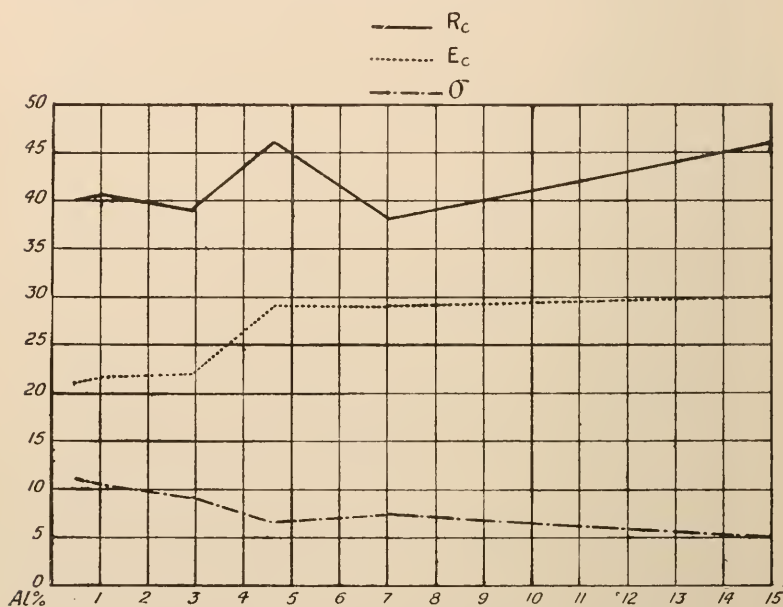


FIG. 29.—Aluminium Steels containing 0.800 per cent. of Carbon.  
Variations of  $R_c$ ,  $E_c$ , and  $\sigma$ .

grammes per square millimetre, while, on the other hand,  $\sigma$  does not appear to be in any way affected.

It is needful to observe that, in the result, the elastic limit on tensile stressing is much less affected by the addition of aluminium.

2. *Steels containing 0.8 per Cent. of Carbon* (Fig. 29).—The influence of aluminium on the characteristics of the shearing test is less important than in the preceding cases, there being

found, indeed, an increase of only 6 kilogrammes when the percentage of aluminium rises from 0.45 to 14.9 per cent. In the same manner the elastic limit, which is more affected by the resistance to shearing (as it rises by 9 kilogrammes), falls to half its amount when the aluminium rises from 0.4 to 14.9 per cent. This steadily maintained character of the

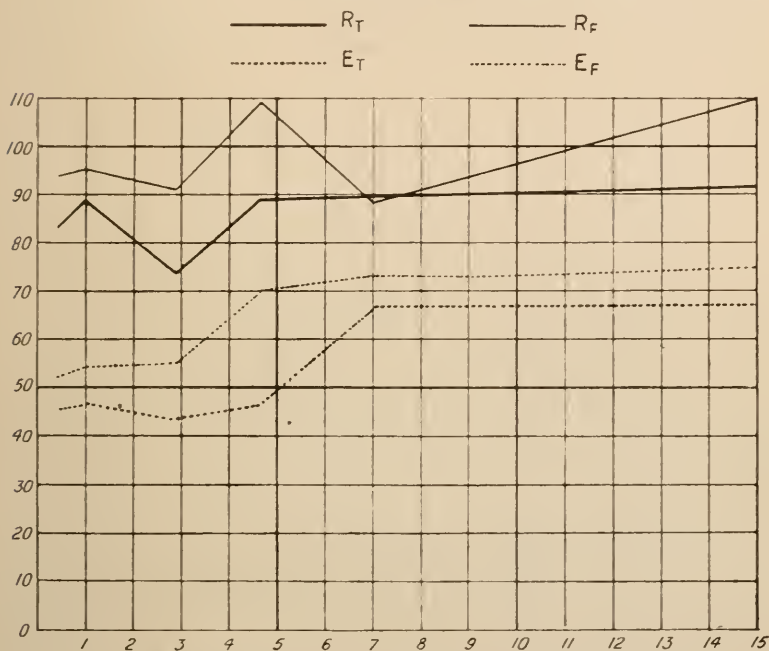


FIG. 30.—Aluminium Steels containing 0.800 per cent. of Carbon.  
Comparison of Tensile and Shearing Tests.

variation in the mechanical properties corresponds fairly closely with the fact that all these steels reveal a pearlitic structure, the aluminium passing into solution in the iron.

#### COMPARISON OF THE RESULTS OF THE TENSILE AND SHEARING TESTS.

The graphs given in Figs. 30 and 31 show that, so far as the tensile strength of the steels containing 0.2 per cent. of

carbon is concerned, the difference between the experimentally established results and those calculated from Frémont's formula steadily increases with the percentage of aluminium, in the case of low percentages of aluminium. The difference is only 3 to 4 kilogrammes. For the steels with 0·8 per cent. there is, generally speaking, no agreement; nevertheless it may be remarked that in both series of steels the difference, with higher percentages of aluminium, between the elastic limit observed on stressing and that calculated

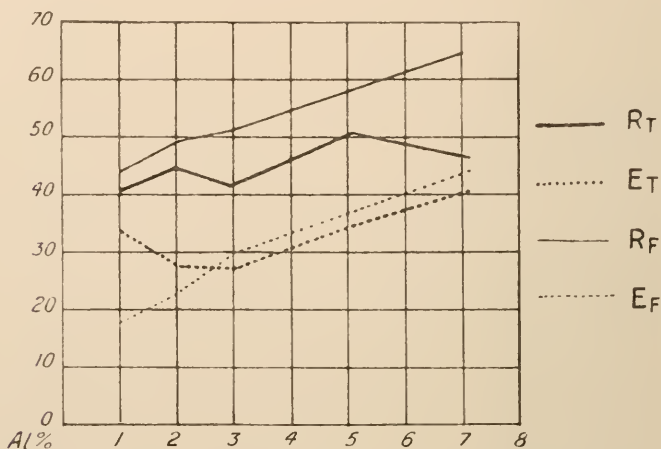


FIG. 31.—Aluminium Steels containing 0·200 per cent. of Carbon.  
Comparison of Tensile and Shearing Tests.

from the shearing tests is very small, and that the variations are fairly similar.

To sum up, it would appear that in the case of aluminium steels Frémont's formula gives results not differing very greatly from those obtained from the tensile tests.

### VANADIUM STEELS.

The chemical analyses and mechanical properties of these steels are shown in Table VI. It will be seen that the tests bore upon two series of steels, one containing but little carbon, and the other about 0·8 per cent. of carbon. The results

TABLE VI.—*Vanadium Steels.*

Description.	Chemical Composition.						Shearing Test.			Tensile Test.			Results calculated by Fémont's Formula.	
	C.	Si.	S.	Ph.	Mn.	Va.	R <sub>u</sub> .	E <sub>c</sub> .	σ.	R <sub>p</sub> .	E <sub>p</sub> .	σ.	R <sub>p</sub> .	E <sub>p</sub> .
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.
1V0.2	0.114	0.105	0.031	0.031	0.125	0.23	23	10	18.5	43.8	30.2	62.5	44	25
1V0.7	0.141	0.304	0.027	0.038	0.445	0.75	30	16	19	57.7	43.4	58.2	65	39
1V1	0.112	0.256	0.021	0.037	0.380	1.04	29	14	18	61.1	45.4	70.8	62	34
1V1.5	0.130	0.248	0.015	0.048	0.380	1.54	24	12	26	56.4	44.8	72.5	48	30
1V3	0.187	0.292	0.025	0.082	0.860	2.98	21	7	33	47.1	26.8	73.8	48	17
1V5	0.382	0.607	0.023	0.067	0.196	5.37	24	8	25	46.5	25.5	61.0	47	19
1V7	0.130	0.109	0.015	0.112	traces	7.39	24.3	10	25.5	43.8	24.8	62.7	48	25
1V10	0.120	0.539	0.016	0.160	"	10.27	26.7	11	27	46.5	27.3	53.1	55	28
8V0.2	0.816	0.326	0.037	0.031	0.445	0.25	55.4	30	7	88.5	43.8	20.3	137	76
8V0.5	0.725	0.409	0.028	0.062	0.555	0.60	50.5	20	10.5	92.3	47.4	22.4	123	51
8V0.7	0.786	0.304	0.031	0.038	0.330	0.80	52	21.5	9	96.2	36.2	19.3	127	54
8V1	0.674	0.248	0.019	0.038	0.300	1.15	43.2	18	10	87.5	58.5	26.2	102	52
8V1.5	0.618	0.292	0.021	0.053	0.340	1.98	38.3	18	12.5	94.9	64.1	31.3	88	44
8V2	0.950	0.421	0.025	0.016	0.224	2.89	44	20	12	91.4	48.1	33.9	105	50
8V3	0.666	0.356	0.022	0.058	0.700	3.06	40	21	10.5	85.2	58.2	28.5	92	53
8V7	0.737	0.745	0.046	0.122	0.309	7.85	26.7	10	17	51.7	28.9	34.3	55	26
8V10	0.858	0.993	0.048	0.049	0.562	10.25	31.3	13	15.5	62.5	36.6	37.5	68	32



yielded the data for the plotting of the curves shown in Figs. 32 to 35.

### VARIATION IN THE RESULTS OF THE SHEARING TESTS IN RELATION TO THE PERCENTAGE OF VANADIUM.

1. *Steels containing 0.2 per Cent. of Carbon* (Fig. 32).—By examining the typical graph, three classes of steel can be recognised.

(a) Steels of which the tensile strength and elastic limit on shearing increase with the percentage of vanadium,  $\sigma$  remaining

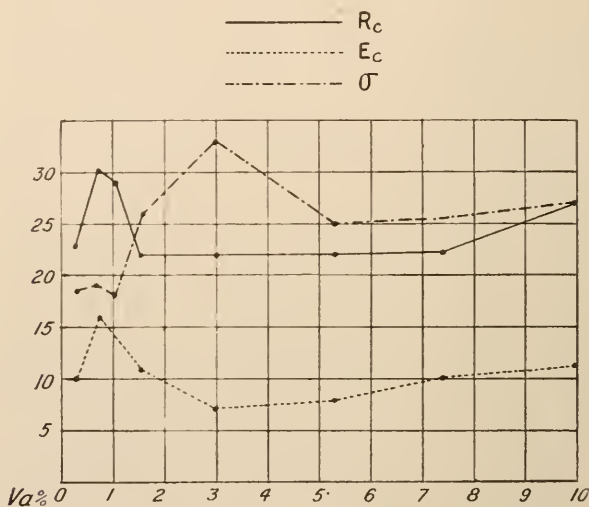


FIG. 32.—Vanadium Steels containing 0.2 per cent. of Carbon.

practically constant. These steels contain up to 1 per cent. of vanadium.

(b) Steels the tensile strength and elastic limit of which decrease with the percentage of vanadium, while  $\sigma$ , under similar conditions, increases rapidly, to the extent of doubling in value. These steels contain from 1 to 3 per cent. of vanadium. Within these relatively restricted percentages  $E_c$  varies from 13 to 7 kilogrammes.

(c) Steels for which the three characteristics  $R_c$ ,  $E_c$ , and  $\sigma$

of the shearing tests have values which are, generally speaking, equivalent. These steels contain over 5 per cent. of vanadium.

2. *Steels containing 0.8 per Cent. of Carbon* (Fig. 33).—The interesting point about these steels is the high tensile strength and elastic limit on shearing, coupled with the low percentages of vanadium. These two factors decrease, but nevertheless

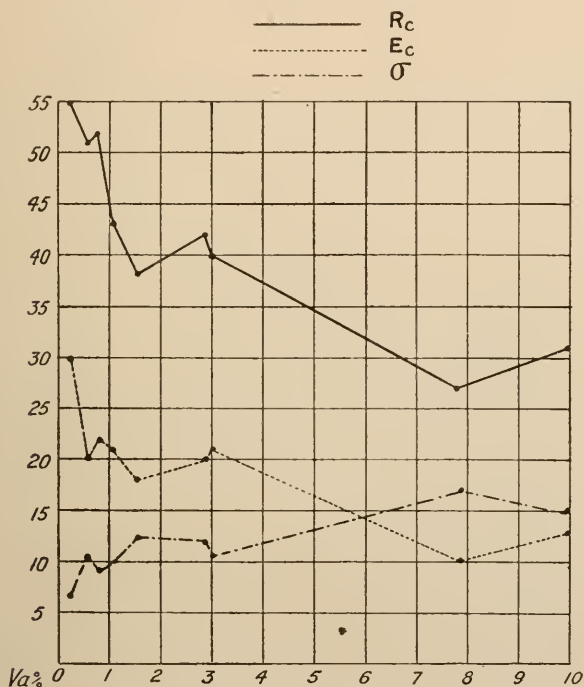


FIG. 33.—Vanadium Steels containing 0.8 per cent. of Carbon.

maintain considerable values as long as the percentage of vanadium does not exceed 3 per cent. With 7 per cent. of vanadium and upwards  $R_c$  remains in the vicinity of 30 kilogrammes, but  $\sigma$  assumes markedly higher values than in the case of steels with low percentages of vanadium. It may also be remarked that the factor  $E_c$  varies strictly in the opposite direction, and nearly proportionately.

## RELATION TO STRUCTURE.

With steels containing 0·2 per cent. of vanadium the three following microstructural groups are clearly distinguishable:—

(1) *Pearlitic Steels*.— $R_c$  and  $E_c$  increase with the percentage of vanadium.

(2) *Pearlitic Steels containing the Double Carbide*.— $R_c$  and  $E_c$  decrease with the percentage of vanadium, whereas  $\sigma$  decreases.

(3) *Steels containing the Double Carbide*.— $R_c$ ,  $E_c$ , and  $\sigma$  vary but little with the percentage of vanadium.

For steels containing 0·8 per cent. of carbon, two groups may be recognised, of which the second is characterised by

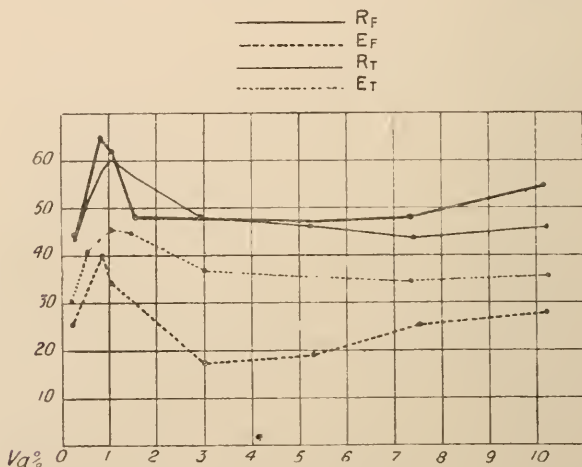


FIG. 34.—Vanadium Steels containing 0·200 per cent. of Carbon.

the fact that it contains the double carbide without pearlite, whereas the first group contains pearlite with or without the double carbide.

#### COMPARISON OF THE RESULTS OF THE TENSILE STRENGTH AND SHEARING TESTS.

1. *Steels containing 0·2 per Cent. of Carbon* (Fig. 34).—The limit, on tensile stressing, is markedly higher in the case

of the whole of these steels than that calculated from the results of the shearing tests. On the other hand, the results of the actual tensile tests found experimentally and those

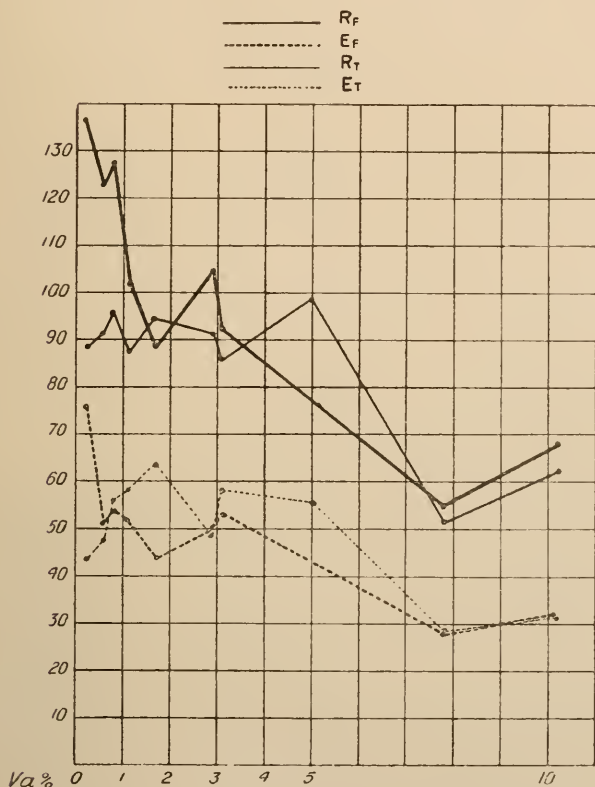


FIG. 35.—Vanadium Steels containing 0.800 per cent. of Carbon.

calculated from Frémont's formula vary in the same direction, and present, in certain instances, a slight divergence.

The fact should not be lost sight of that all these steels possess tensile strengths comprised within 40 and 60 kilogrammes per square millimetre—that is, differing but slightly from those of steel containing normal amounts of carbon.

2. *Steels containing 0.8 per Cent. of Carbon* (Fig. 35).—There may be seen at the outset an enormous difference

TABLE VII.—*Molybdenum Steels.*

Description.	Chemical Composition.						Shearing Test.			Tensile Test.			Results calculated by Frémont's Formula.	
	C.	Si.	Ph.	S.	Mn.	Mo.	Rc.	Ec.	$\sigma$ .	Rf.	Ev.	N.	Rf.	Ev.
1Mo0.5	Per Cent. 0.188	Per Cent. 0.117	Per Cent. 0.018	Per Cent. 0.009	Per Cent. 0.070	Per Cent. 0.45	Kilos. 26	Kilos. 13.6	Kilos. 12	Kilos. 48.9	Kilos. 37.6	Kilos. 69.3	Kilos. 53	Kilos. 34
1Mo1	0.158	0.110	0.018	0.032	0.100	1.00	22.5	8.8	19	64	39.5	66.5	46	22
1Mo2	0.138	0.128	0.021	0.009	0.168	2.20	26.4	16	10.5	82.8	67.7	12.1	54	40
1Mo5	0.289	0.117	0.026	0.039	0.500	4.50	39	27	11	130.6	103.2	7.5	90	69
8Mo0.5	0.735	0.210	0.021	0.032	0.260	0.50	44.2	26.4	8.5	115.2	82.8	7.5	105	66
8Mo1	0.811	0.019	0.040	0.018	0.396	1.21	51.5	36.8	5.5	120.5	78.3	5.6	126	92
8Mo2	0.814	0.175	0.016	0.034	0.300	1.98	53.4	42.0	4.5	143.1	101.7	5.2	134	105

between the ascertained and calculated results. For the steels containing less than 1 per cent. of vanadium—that is to say, the pearlitic steels—the difference amounts to as much as 40 kilogrammes per square millimetre. As soon as the double carbide makes its appearance this difference diminishes considerably, and the two curves representing the variations of  $R_F$  and  $E_T$  merge together similarly to the two curves  $E_F$  and  $E_T$ .

The fact should particularly be noted that the disparity in results of the tensile tests and those calculated from the shearing tests manifests itself in the region in which the steels, being pearlitic, possess the same microstructure as ordinary carbon steels. The values relating to tensile strength are, however, fairly high (85 to 95 kilogrammes per square millimetre).

### MOLYBDENUM STEELS.

It was only possible to study a very small number of molybdenum steels, as it was impossible to exceed 5 per cent. of molybdenum for steels with a low percentage of carbon, and 2 per cent. for steels with 0.8 per cent. of carbon. The figures relative to the chemical analyses and the mechanical tests are shown in Table VII.

It will be at once remarked that, apart from the abnormal result found in the case of steel 1Mo1, the tensile strength and elastic limit on shearing increases markedly with the percentage of molybdenum. So far as  $\sigma$  is concerned, it diminishes to a considerable extent in the case of steel containing 0.8 per cent. of carbon.

If the results of the tensile tests be compared with those calculated in accordance with Frémont's formula, it will be seen that the curves of variation (Figs. 36 and 37) are practically parallel, and even in the case of steels containing 0.8 per cent. of carbon, a very remarkable degree of agreement may be observed, considering the very high tensile strength of these steels (115 to 143 kilogrammes per square millimetre), whereas, in the preceding series of steels, once these values are



attained, a considerable divergence is always observed. It may be remarked that the latter steels contain the double carbide.

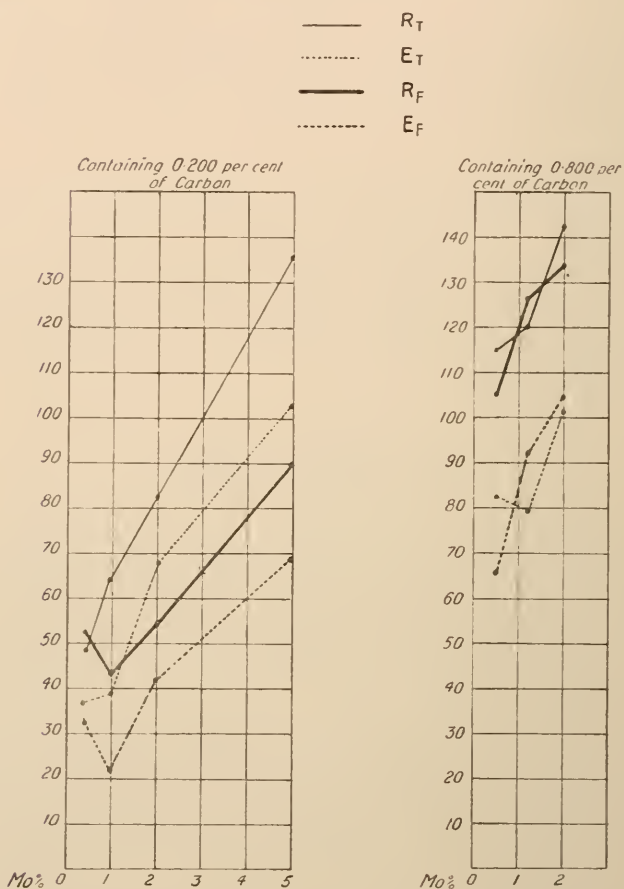


FIG. 36.—Molybdenum Steels. Comparison of Tensile and Shearing Tests, (Frémont's formula.)

FIG. 37.—Molybdenum Steels. Comparison of Tensile and Shearing Tests. (Frémont's formula.)

### MISCELLANEOUS STEELS.

Experiments were also carried out on a variety of steels containing titanium, silicon, boron, and tantalum, but each series contained only a small number of samples, so that it

was deemed advisable to group the analyses and mechanical constants of these steels together in Table VIII.

### TITANIUM STEELS.

The tensile strength and the elastic limit on shearing increase slowly as the percentage of titanium rises. The divergence between the results found on tensile testing and those calculated from Fremont's formula are but small, and at times a remarkable degree of concordance is found. It should not be forgotten, however, that all these steels are pearlitic.

### SILICON STEELS.

The tests were carried out on four samples only. The agreement between  $R_c$  and  $R_f$  in the steels 1S1 and 8S0.5 may be observed, but as regards the elastic limit, there is a marked divergence between  $E_c$  and  $E_f$ .

### BORON STEELS.

The resistance to shear, and, in particular, the elastic limit on shearing, increase rapidly with the percentage of boron in the steel containing 0.25 per cent. of carbon, but this appears partly due to the increase in the percentage of manganese and silicon which these steels contain. In any case, there may be remarked an important divergence between the figures of the tensile test of the steel containing the special constituent, borocarbide of iron, described by Guillet. Similarly, it is of interest to note the rapid decrease of  $\sigma$ .

### TANTALUM STEELS.

The comparison of  $R_c$  and of  $R_f$  is fairly satisfactory for the four tantalum steels experimented on, but this is not the case as regards  $E_c$ . In any case, the influence of the tantalum on the characteristics of the shearing tests is small. Micrographically all these steels are pearlitic.

TABLE VIII.—*Miscellaneous Steels.*

Description.	Chemical Composition.						Shearing Test.			Tensile Test.			Results calculated by Frénoit's Formula.	
	G.	Si.	S.	Ph.	Mn.	Special Element.	Rc.	Ec.	$\sigma$ .	R <sub>T</sub> .	E <sub>T</sub> .	N.	R <sub>F</sub> .	E <sub>F</sub> .
<i>Titanium.</i>														
1Ti0.5	Per Cent. 0.112	Per Cent. 0.047	Per Cent. 0.015	Per Cent. 0.018	Per Cent. 0.189	Per Cent. 0.415	Kilos. 20.4	Kilos. 6.8	Kilos. 25.5	Kilos. 40.7	Kilos. 33.9	Kilos. 68.4	Kilos. 38	Kilos. 17
1Ti1	0.106	0.163	0.015	0.020	0.140	0.879	20.8	8.8	22	45.2	37.6	67.5	39	22
1Ti2	0.137	0.105	0.007	0.020	0.170	1.398	22.8	9.2	22.5	48.2	36.1	62.1	45	23
1Ti3	0.135	0.146	0.017	0.010	0.310	2.570	23.8	11.2	21	45.2	34.6	68.4	48	28
8Ti0.5	0.760	0.292	0.015	0.015	0.230	0.325	41.5	23.2	10.5	91.1	54.9	19.0	100	58
8Ti1	0.695	0.256	0.024	0.025	0.240	0.640	40.5	24	10	94.1	52.6	28.4	97	60
8Ti2	0.624	0.350	0.011	0.021	0.230	0.720	37.1	20.4	9	87.7	53.3	36.7	87	51
8Ti3	0.611	0.411	0.025	0.015	0.270	2.575	42.2	22.4	10.5	90.4	58.8	34.7	102	56
8Ti5	0.635	0.346	0.018	0.013	0.315	4.630	37.8	24.0	11.5	89.8	57.8	34.2	89	60
8Ti10	0.650	0.163	0.011	0.016	0.450	8.710	46.9	26.8	12.0	117.5	62.5	29.7	116	67

<i>Silicon.</i>														
1S1	0.208	0.932	0.020	0.024	traces	...	27.4	10.4	17	58.7	37.6	59.2	57	26
1S2	0.177	1.46	0.012	0.032	0.275	...	28.5	12.4	23	56.5	45.2	63.9	60	31
8S0.5	0.878	0.433	0.013	0.057	0.730	...	47.7	29.2	5.5	115.2	62.5	10.4	115	73
8S2	0.968	2.09	0.022	0.032	0.407	...	47.7	25.2	11	105.4	76.8	0	115	63
<i>Boron.</i>														
2B0.2	0.180	0.232	0.012	0.023	0.076	0.205	21.8	7.6	19.5	37.5	20.2	57.5	41	19
2B0.5	0.224	0.163	0.015	0.015	0.292	0.462	21.8	8.0	16.5	39.6	20.2	55	41	20
2B1	0.207	0.792	0.014	0.013	0.600	0.844	31.3	13.2	14	50.1	29.8	26.8	68	33
2B2	0.281	0.641	0.005	0.018	0.600	1.514	32.7	19.2	7.2	51.7	31.5	4.4	72	48
5B0.2	0.475	0.283	0.020	0.020	0.370	0.155	33.4	20.8	10	51.0	34.5	27.3	74	52
5B0.5	0.595	0.292	0.016	0.023	0.295	0.406	32	19.2	8.2	54.0	39.0	22.8	70	48
<i>Tantalum.</i>														
2Ta0.2	0.120	0.120	traces	traces	0.190	0.09	21.1	8.4	21	41.5	29.8	67.4	39	21
2Ta0.5	1.70	0.190	"	"	0.150	0.15	21.5	9.2	18	42.6	30.4	68.8	40	23
2Ta1	0.180	0.240	"	"	0.220	0.60	21.5	10	19	45.3	31.1	67.4	40	25
2Ta2	0.160	0.160	"	"	0.230	1.05	23.2	10	20	47.8	31.5	62.3	45	25

## GENERAL CONCLUSIONS.

The principal conclusions that may be drawn from the whole of the determinations may be summed up briefly as follows:—

The results on shearing are, like those of the tensile tests, influenced to a considerable degree by the structure, and may serve to distinguish the different types of steel, *e.g.* pearlitic, martensitic, polyhedral, &c.

The shearing test may therefore serve, like the tensile test, to classify these steels.

It may be asked whether the shearing test is capable of replacing the latter. To supply an answer, it would be necessary that there should be in existence formulæ correlating, for all these steels, the characteristic results of the tensile tests with those of shearing.

The Frémont formulæ ascertained for the ordinary structural steels are not applicable in the majority of cases to the special steels. The relation between the tensile test and the shearing test depends both on the special element added and on the structure of the steel. Even in the case of steels where the difference between the results of the tensile test and that calculated from Frémont's formula is small, it will be seen that this difference becomes a minimum for an ascertained value of the tensile strength, which, in addition, varies according to the element added. It is nevertheless possible, within certain limits of tensile strength, to find linear formulæ correlating the results of the two tests, as was shown in the case of the nickel steels, in which the number of determinations was greater than for the other series; but to ascertain those relations, which are purely empirical, it is necessary to rely upon a very large number of experiments, and for this reason the number of formulæ has not in this investigation been increased.

It would appear that directly it is sought to include steels of the same type, the tensile strength of which varies within wide limits, it becomes necessary to have recourse to a formula containing three terms. Even then it is not possible to employ a single formula only, as the relation between the

resistance to shearing,  $R_c$ , and the resistance to tensile stress,  $R_t$ , depends on the composition of the steel. Thus Frémont's formula, which is practically applicable to all the nickel steels containing 0·120 per cent. of carbon, can no longer be employed in the case of steels containing 0·8 per cent. of carbon, particularly when  $R_t$  reaches 120 kilogrammes per square millimetre. This is not owing to the high value of  $R_t$ , for the formula still serves for molybdenum steels possessing a tensile strength of 130 kilogrammes per square millimetre. It is not possible either to cherish the hope of combining, under one law, all the steels possessing the same microstructure. Thus, with the polyhedral steels the Frémont formula gives results not very far removed from the truth, but with nickel steels it leads, in the case of manganese steels, to exaggerated values.

From the foregoing it may be seen that to establish a relation between the tensile and shearing tests of special steels, it is necessary to take into account—

- (1) The nature of the element added to the steel;
- (2) The structure of the steel, and
- (3) The limits of tensile strength within which the formula becomes applicable.

It is beyond contest, and the general appearance of the curves demonstrates the fact, that the characteristics of the tensile tests and those of shearing depend upon variables common to both, but the formula becomes complicated by reason of the intervention of other variables, which differ in each case, and the influence of which render any simple relation, applicable to a wide range of steels, impossible.

Even for a series of metals of similar properties but of very variable tensile strength the formula combining  $R_t$  with  $R_c$  will possess at least three terms, and Frémont's linear formula represents, in any specific instance, the equation of a chord of the curve  $R_c = f(R_t)$ . Nevertheless, this formula, which is applicable to the ordinary steels, allows of the improvement conferred upon the shearing qualities by the addition, to these steels, of additional elements being taken into account. It is for this reason that the martensitic steels, the polyhedral manganese steels, and, in particular, the pearlitic vanadium steels containing 0·8 per cent. of carbon, are strongly resistant



to shearing, while, on the other hand, the polyhedral nickel steels and the chromium steels are slightly inferior, and the tungsten and aluminium steels distinctly so.

If the shearing test does not admit of the supersession of tensile testing, it does not follow that it is inferior to the latter. On the contrary, it brings out other properties, and, in addition to the advantages resulting from the ease with which the test-pieces can be prepared, it possesses the superior advantage, allows of the homogeneity of the metal being ascertained, owing to the small size of the test-pieces and the possibility of renewing the test on sections close together, thus eliminating the influence of local defects, whereas the tensile test only yields an average result. This is evidently an important consideration from the point of view of the application to be made of the steel, but a disadvantage from the point of view of research because of the intervention, pell-mell, of a host of factors; the inequality in chemical composition and in the heat treatment of the sample, and all the special accidents, cracks, hollows, &c., which help to falsify the results. The test has nevertheless its own particular application, which is both old established and widespread.

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## PART II.

## I. GENERAL CONSIDERATIONS REGARDING THE ELECTRICAL RESISTANCE OF STEELS.

The investigations hitherto made on the electrical resistance of steels may be grouped into three categories, according to the object in view :—

1. Those which have been concerned with the relation between the electrical resistance and the chemical constitution, as, for example, the researches of Matthiessen, Johnson, Hopkinson, Osmond, Stead, Ebeling, Mathews, and, in particular, those of Le Chatelier, of Barrett, Brown, and Hadfield, and of Benedicks.

2. Those which have dealt with the variation of electrical resistance with temperature, amongst which may be mentioned those of Hopkinson, Morris, Le Chatelier, Fournel, and Boudouard.

3. Those which have dealt with the influence of heat treatment, quenching, and annealing, on the electrical resistance. Particular mention may, in this connection, be made to the work of Strouhal, Osmond, Rydberg, and, more recently, Maurer.

This classification has, it need hardly be said, no hard and fast application, and, in many of the investigations, the influence of thermal treatment and of the chemical composition have been studied simultaneously. The influence of temperature on the electrical resistance of steel has not been dealt with at all in the present work, as such interest as it possesses centres chiefly in the possibility of ascertaining the transformation points, thus completing, often in a most useful manner, the indications obtained by the calorimetric method.

## 1. INFLUENCE OF THE CHEMICAL COMPOSITION.

As regards chemical composition, Le Chatelier has found that :—

1. The resistance increases with the percentage of carbon in the case of annealed steels.

2. For every 100 atoms of an alloy, one atom of silicon increases the resistance by 7 microhms; one atom of manganese increases the resistance by 5 microhms; and one atom of nickel increases the resistance by 3 to 5 microhms.

3. Chromium, tungsten, and molybdenum have but slight influence on the resistance.

4. One atom of hardening carbon produces an increase in the resistance, practically equal to that of silicon.

In discussing these results and those of the important investigations of Barrett, Brown, and Hadfield, Benedicks has laid down the following law: *Equiatomic solid solutions of iron possess equal resistances*, and he has verified this law, more or less closely, for solid solutions containing the following elements:—

Carbon,	Phosphorus,	Cobalt,	Molybdenum,
Aluminium,	Chromium,	Nickel,	and Tungsten,
Silicon,	Manganese,	Arsenic,	

and has established the following formula:—

$$\rho = 7.6 + 26.8 \Sigma C \text{ microhms per square millimetre,}$$

where  $\rho$  is the electrical resistance of the steel, 7.6 the electrical resistance of pure iron, and  $\Sigma C$  is the sum of the values, in terms of carbon, of the elements dissolved in the iron. The "carbon value" is obtained by dividing the percentage found on chemical analysis by the atomic weight of the element and multiplying the result by 12, the atomic weight of carbon:—

$$\Sigma C = C + \frac{12.0}{28.4} \text{Si} + \frac{12.0}{55.0} \text{Mn} + \dots$$

An attempt was made to verify this formula in the case of the steels which were employed for the shearing tests, the analyses of which have already been given in the first part of this report. The results of the calculations are not recorded for the steels with low percentages of the special elements. Sometimes they agreed with the law, and at others the results were very far removed from the calculated resistances.

Should it therefore be concluded that the chemical analyses are wrong? This would not be impossible, but only a fresh

series of analytical determinations could settle this question. When high percentages of the special element are present the formula is found to be completely out of agreement. It is well, therefore, as regards this matter, to note the limitations placed by Benedicks himself on the application of the formula. He says:—

“This applies here to dilute solutions. It is, as a matter of fact, difficult to fix the upper limit of the validity of the formula. Probably it would exceed  $\Sigma C = 2$  per cent. but not 3 per cent. This means that it could not, probably, be applied for concentrations exceeding one atom dissolved to every eight atoms of carbon.”

The correctness of this remark will be seen later, as, in the steels under investigation, apart from those containing percentages of 0·5 and 0·7, higher amounts than 1 per cent. of the principal added metal were present. That is to say, that except perhaps for the first or second steel of each series, the percentages of the special element are, in amount, distinctly higher than those of the ordinary impurities present in a steel (manganese, silicon, sulphur, phosphorus) the influence of which they mask, so that the general form of the curves traced indicates the behaviour of the variations in resistance due to the chief elements added. The accessory variations which are observed, and render the track of the curves at times rather regular, are actually due to the secondary impurities.

Apart from this law which expresses, as regards weak solutions, the influence of elements in solid solution in iron, Benedicks found that iron carbide, or cementite, does not appear to exert any influence on the resistance so long as it is isolated within the mass of the iron. It will thus be seen that the structure of a steel has a considerable influence on the nature of the variations in resistance due to the addition of elements to iron.

## 2. INFLUENCE OF THE HEAT TREATMENT.

One of the results of hardening is the throwing into solid solution of a certain quantity of carbon, which has the effect of increasing the electrical resistance. Amongst the experi-

mental results published on this subject may be quoted the following:—

I. Those of Benedicks, which, so far as they bear on the subject, are collected together in the following table:—

Percentage of Carbon.	Electrical Resistance in Microhms per Cubic Millimetre.	
	Annealed Steels. Per Cent.	Hardened Steels. Per Cent.
0.08	10.51	10.90
0.16	12.59	13.6
0.23	13.74	15.4
0.33	14.67	17.2
0.38	15.11	18.3
0.45	24.03	28.99
0.55	27.54	34.36
0.62	20.82	30.6
0.90	20.44	36.94
0.95	21.11	38.6
1.20	20.99	34.36
1.35	21.70	36.94

II. The results found by Maurer may be summarised as follows:—

Percentage of Carbon.	Electrical Resistance at 800°, in Microhms. Per Cent.	Hardened Steels.	
		Hardening Temperature. Degrees.	Electrical Resistance Calculated to that of the Annealed Bar. Per Cent.
0.4	13.9	1000	1.15
0.83	14.2	800	1.43
	14.4	1100	1.83
1.2	18.4	800	1.74
	21.6	1100	2.26

It may be seen that the electrical resistance increases with the increase in the percentage of carbon, and with the more or less complete passage of that element into solution. It is for this reason that hardening at a high temperature yields a higher electrical resistance than hardening carried out at a lower temperature. Besides this, in Benedicks' work the steel containing 1.35 and 1.5 per cent. of carbon respectively,



quenched at a red heat (the temperature is not indicated) gain electrical resistances of 49·6 and 50·6 microhms respectively.

It may therefore be said, with Benedicks, that the electrical resistance furnishes an accurate indication of the percentage of hardening carbon. This is also confirmed by a study of the results of annealing. The experiments of Strouhal and Barus, carried out on steels the chemical composition of which is not stated, show that the electrical resistance decreases in proportion as the temperature of the reheating rises. The present author had undertaken, at the outset of this investigation, researches with the object of determining these points accurately, but having had knowledge of Maurer's work he abandoned this project. There may, however, be quoted, from amongst those preliminary experiments, the following results, for they differ from those of Maurer to the extent that they were obtained by working with a fixed temperature of reheating and a variable period, whereas Maurer's experiments were made by progressively raising the temperature of reheating.

A steel containing 0·8 per cent. of carbon was quenched at 850°, and then placed in a bath of lead, formed by a vertical tube filled with molten lead and heated electrically by means of a coil of nickel wire covered with asbestos. The temperature of the bath was 480° ± 5°, and the values of the specific resistances of the bars were as follows:—

	Microhms.	
After quenching . . .	34·4	Martensitic structure with traces of troostite.
After reheating 5 minutes .	21·6	Sorbitic structure.
„ „ 15 „ .	21·3	„ „
„ „ 1 hour .	19·6	Structure of very fine pearlite.
„ „ 2 hours .	19·6	„ „ „

At the end of a certain period of reheating the electrical resistance no longer varies except to a very slight extent, this phenomenon manifesting itself from the time of the appearance of the sorbite. The electrical resistance is capable, therefore, to a certain extent, of serving as a measure of the degree of annealing.\*

\* L. Guillet and A. Portevin, "Note on the Tempering Colours," *Revue de Métallurgie*, 1909, p. 102; A. Portevin, "Researches on the Relation between the Scale of Tempering Colours and that of Temperature," *Bulletin de l'Association pour l'essai des matériaux de Construction*, November 1908, p. 12.



Thus it may still be seen that the modifications induced in the electrical resistance by the heat treatment are intimately correlated with the modifications in the structure of the steel. The law of the variation differs considerably according to whether the carbon is in solution (hardened steels) or whether it is in the state of carbide. This question deserves to be studied in detail, as it is of great importance from the point of view of the interpretation of the results of experiments.

### 3. INFLUENCE OF THE MICROSTRUCTURE.

The laws formulated in the case of steels by Benedicks afford but a particular instance of those which govern the variations in the electrical resistances of alloys. The relation between conductivity and constitution has been specially studied by Le Chatelier and by Guertler; the latter was led, by comparing the estimations of conductivity and experiments on the structure of over twenty-five alloys, to enunciate the following laws, which do not differ from those laid down by Le Chatelier.

1. Alloys the electrical conductivity of which is a linear function of the volume concentration of two elements of the alloy, have no appreciable miscibility (0.05 per cent.) in the solid state and *vice versa*.

2. The curve of the electrical conductivity of alloys forming a continuous series of mixed crystals extends continuously from one of the pure components to the other while preserving a low minimum, and reached, by a rapid rise, the values of the electrical conductivity of the pure components themselves, so that, with a low degree of concentration of a given component in the mixed crystals, a fresh addition causes a lowering of the curve, greater, beyond all comparison, than that which would occur in the case of a higher degree of concentration, and *vice versa*.

3. For a limited degree of miscibility of the components in a crystallised state it is, for saturated concentrations of mixed crystals, Law I. which prevails as between pure components, and Law II. which obtains between pure metals and saturated mixed crystals.

In a translation of this work, published in 1907,\* the author of the present report drew attention to the fact that these laws might be expressed more concisely as follows:—

When there is but one phase resulting from the miscibility of two components (simple bodies or compounds) the conductivity varies to a considerable degree as a function of the degree of concentration, presenting a considerable lowering, which starts from the two pure components; when there are two phases the conductivity of the mixture is a linear function of the conductivity of each of the phases.

The electrical conductivity being the reciprocal of the specific resistance, it is easy to deduce from these laws those of the variation of the resistance as a function of the constitution.

It may thus early be seen that, even in the case where, with constant percentages of foreign elements present, solid solutions are in respect of steels involved, Benedicks' laws are only applicable for low percentages. Indeed, the curve of the conductivity in terms of the chemical composition resembles, in the case of solid solution, a parabola with a vertical axis, the apex of which is somewhat flattened. From this it results that the electrical resistance varies greatly to begin with, starting from one of the pure metals to present, later on, slighter variations, a condition which obviously cannot be expressed by any linear formula. That of Benedicks is but the equation of the tangent of origin, or of a chord of this curve.

In the present case, which relates to the special steels, it would be obviously rash to extend these laws, formulated for binary systems, to ternary systems containing iron + carbon + special elements. It does not, however, appear too much to admit that, as in the case of binary alloys, the nature of the variations of conductivity and of electrical resistance in terms of the constitution will differ greatly according as the addition of the special element has the object of increasing the degree of concentration of a solid solution, or the quantity of a constituent of constant concentration, that is to say, of a definite compound. In the same way quenching will produce a marked

\* *Revue de Métallurgie*, 1907, p. 670.

increase in the electrical resistance if this treatment leads to the throwing into solution of an element of the steel (carbon or the special element). It should not, indeed, be forgotten that, in a ternary system, the existence of two phases within a certain range of composition has not the same consequence as in a binary system, namely, the invariability of the composition of these phases, and, as a result, the linear variation of the electrical conductivity within this range.

To sum up, it will be seen—and this is the object of the criticism of these different investigations—that the microstructure of the alloys plays an important part in the investigation of the electrical properties, and thus the nature of the variations in resistance that have been observed, not only in terms of the composition, but also in terms of the heat treatment, should be interpreted by taking into account the structure, or, in other words, studying the micrography of these alloys.

## II. EXPERIMENTAL APPLIANCES.

### 1. THE PRINCIPLES OF THE METHOD.

In order to ascertain the electrical resistance of steels, the fall in potential between two points in the bar under investigation is measured and compared with that between two points in a standard bar subjected to the same current.

The test-bars were turned to a diameter of 8 millimetres and were 120 millimetres in length. Very hard martensitic steels, or those containing the double carbide were dressed wholly on a grindstone, and as this grinding was carried out by hand the diameter often differed from 8 millimetres by some tenths of a millimetre, but the figures obtained were rectified in the following manner:—

Let  $x$ ,  $d$ , and  $s$  be the specific resistance, diameter, and sectional area of the bar under investigation, respectively,  $l$  the length between the points or distance through which the fall of potential of the bar is to be measured, and  $\rho$ ,  $D$ ,  $S$ , and  $L$  the same quantities in the standard bars. If  $\delta$  and  $\Delta$  be

the observed deviations of the galvanometer for the same current traversing both bars, we have—

$$\frac{\delta}{D} = \frac{r}{R},$$

where  $r$  and  $R$  are the resistances of the two bars, or

$$r = \frac{x l}{s} \text{ and } R = \frac{\rho L}{S}.$$

This gives

$$\frac{\delta}{\Delta} = \frac{x l D^2}{\rho L s d^2},$$

and

$$x = \frac{\rho L}{\Delta l D^2} \delta d^2.$$

If  $l$  and  $L$  be kept constant during each test, and if the strength of current be each time regulated so as to secure in each case, the same deviation  $\Delta$  on the standard bar we have—

$$\frac{\rho L}{\Delta l D^2} = K \text{ and } x = K \delta d^2.$$

In the case of the diameters of the bars and the distance of the points between which the fall in potential is measured being the same for both bars we have—

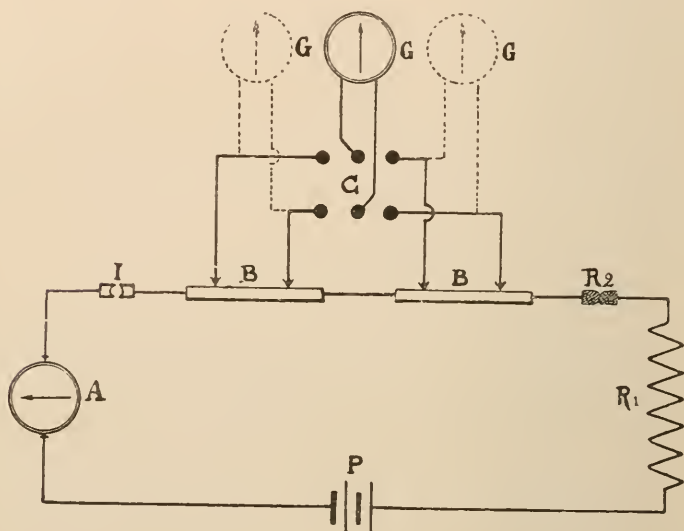
$$x = \frac{\rho \delta}{\Delta}.$$

If the strength of current be chosen so that the deviation  $\Delta$  may be registered on the galvanometer scale by the same number as that expressing  $\rho$  in microhms per cubic centimetre we have  $x = \delta$  and it is possible to read off the specific resistance of the test-bar direct.

The arrangement of the installation is shown in Fig. 38. The electric current from an accumulator battery  $P$  passes successively through resistances  $R_1$  and  $R_2$  which serve to regulate it, and through the two bars  $B$ ,  $B_1$  and an ammeter  $A$ . A key ( $I$ ) allows of the current being turned off or on at will.

The adjustment of the current takes place in two stages; first, at the commencement of each series of tests, by means of the liquid resistance  $R_2$ , made by two carbons immersed in

a soda solution; and by noting the ammeter A the current is adjusted to about the amount required. This varies from one experiment to another owing to the differences in contact resistance in the parts of the apparatus which conduct the current to the ends of the bars  $B_1, B$ . It is therefore necessary in the second place to regulate the strength of the current accurately, which is done by means of the resistance  $R_1$ . The latter consists of two battery carbons held tightly against



A, Ammeter. C, Galvanometer. P, Accumulator.  $R_2$ , Carbon resistance.  
B, Steel bars. I, Switch.  $R_1$ , Liquid resistance.

FIG. 38.

each other by a vice of small pitch. By turning the screw, the pressure of contact between the carbons can be varied, and a very convenient mode of regulating the current is thus secured. During this adjustment the ammeter A is disregarded, but the deviation of the galvanometer is read, as this measures the difference in potential of the standard bar. This contact resistance is indicated by the letter R in Fig. 40, which shows the details of the apparatus as finally adopted.

## 2. MEASUREMENT OF THE FALL OF POTENTIAL IN THE BARS.

Generally speaking, the fall in potential was taken, both in the standard bar and in the test-bars, between two points 100 millimetres apart from each other. At the commencement of the investigations the apparatus employed was as follows (Fig. 39):—A graduated steel guide carries two small vulcanised fibre riders pierced by brass pins furnished with terminals. The two pins have blunted points 100 millimetres apart. The two terminals having been connected up with those of a galvanometer, the appliance was slipped over the

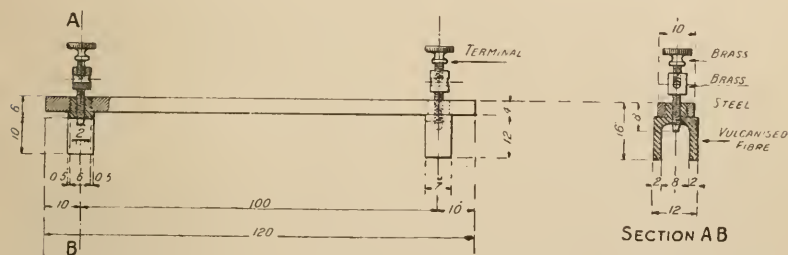


FIG. 39.

bar, and the current applied to the bar by two terminal screws. The disadvantage of this arrangement was that it was necessary to steady the apparatus by hand, and therefore the resulting variable pressure recorded itself by variations in the contact resistance of the pin points with the surface of the bars, and caused fluctuations in the galvanometer readings, added to which the brass pin points became gradually blunted, and the readings therefore varied, for the same bar, from one experiment to another. Although these variations were but small, the use of this apparatus was abandoned in favour of one in which the two following improvements were introduced. The current, instead of passing through the brass points, was made to traverse two hardened steel knife-edges, and the bar was laid, under conditions of constant pressure, across these knife-



edges. The apparatus, thus modified, is shown in Fig. 40. The current is applied at the terminals A, A, flows through the carbon contact resistance R and is conducted to the hammer heads M, M. These hammer heads rotate on an axis supported by the short columns, C, C, which carry hooks attached to the springs, D, D. These springs press the hammer heads against the bars, B, B, which lie across the hardened steel knife-edges. The supports of these knife-edges pass into pieces of vulcanised fibre F, which play the part of insulators and also serve to keep the bars laterally steady in such a manner that their axes are always normal to the direction of the knife-edges. The apparatus is arranged so as to be capable of simultaneously

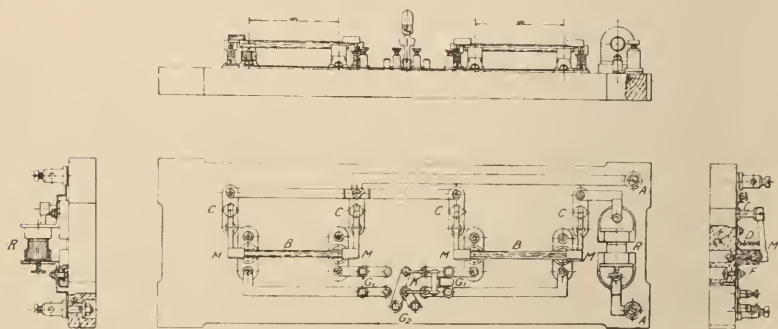


FIG. 40.

measuring the two deviations by connecting two galvanometers in circuit with the terminals  $G_1$ , or of measuring them one after another by employing a single galvanometer connected with the terminals  $G_2$  of the commutator K. The two methods were employed, for comparison, with the object of finding out whether any variations of current took place during the period between two readings. In the first instance (Fig. 41) two Siemens and Halske millivoltmeters were employed, and in the second instance, in order to have an adjustable degree of sensitiveness, a Desprez-d'Arsonval galvanometer coupled up as shown in Fig. 42 was used. In order to dispense with the mirror placed below the graduated scale, which serves to reflect the rays from a luminous source on to

the mirror of the galvanometer, the graduated scale was fixed to the extremity of a reflector formed by a Nernst lamp and a converging lens. By this means a powerful light is obtained



FIG. 41.

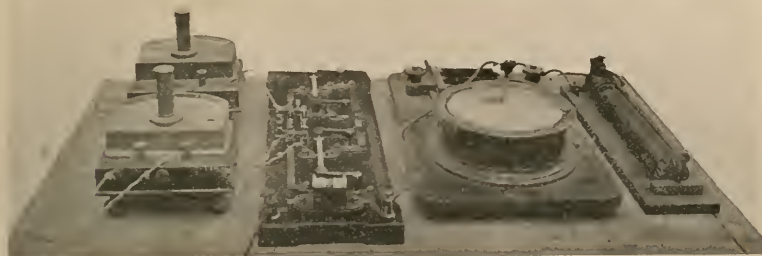


FIG. 42.

which allows of the apparatus being used in bright daylight, besides which the adjustment of the apparatus can, thanks to the omission of a mirror, be effected with great rapidity.

The measurement of the specific resistance of the standard bars was carried out by the Thomson bridge method, at the central Electrical Laboratory of Paris. The results found for the two bars employed were as follows:—

	Resistance in Microhms. Per Cent.	Temperatures. Degrees.
No. 1 Bar, 4N30 . . . . .	82·6	17
No. 2 Bar, 8T5 . . . . .	28·1	18

It was decided to take two standard bars in order, when using the Desprez-d'Arsonval galvanometer, to be able to employ the whole length of the graduated scale for each series to determinations. For this reason, in the majority of the cases the following co-efficients were adopted:—

For Standard Bar 1 . . . . .	K=0·052
„ „ „ 2 . . . . .	K=0·027

When bars could be obtained the diameters were within  $\frac{1}{20}$  millimetre of the size required, 8 millimetres, a Siemens-Halske millivoltmeter was employed in preference, the current being regulated so as to obtain a deviation of 82·6 millimetres on the No. 1 standard bar. In such cases  $x=d$  and therefore it was possible to read off the resistance in microhms direct, by observing the deviation in millivolts registered by the galvanometer.

### 3. TEMPERATURE OF THE EXPERIMENTS.

The experiments were carried out at temperatures varying between  $16^{\circ}$  and  $23^{\circ}$ , and for each series of experiments the temperature is but little noticeable. The heating effect caused by the passage of the current is inappreciable; although sometimes a slight local rise of temperature was detected at the point of contact between the bars and the hammers. In such cases the time of the experiment was prolonged in order to ascertain if this rise of temperature would affect the resistance found, but no appreciable difference was ever detected

even after 15 minutes' flow of current. As the duration of a test was never more than 2 minutes, this source of error may therefore be neglected.

The experiments on each bar were, in every instance, carried out at least in duplicate, and were repeated several times whenever accidental causes led to much difference in the readings.

The bars were kept in tall glass jars filled with quicklime in order to avoid any corrosion from atmospheric causes.

#### 4. METHOD OF HARDENING THE SAMPLES.

At least two series of experiments were carried out on each group of the special steels, one being on the normal steels; that is, those which had undergone the ordinary commercial process of annealing, and the other on the steels as hardened. The special temperature conditions of hardening are given in the case of each group of steels, but the precautions ordinarily observed were as follows:—

With the object of avoiding, as far as possible, oxidation, or the decarburisation of the samples, which is of great importance both from the point of view of the absolute resistance value and that of the contact resistance, the employment of direct-fired heating furnaces and muffles was dispensed with and saline baths substituted. The salt employed was potassium chloride, which has the advantage of melting at a relatively low temperature ( $735^{\circ}$ ), and of being, therefore, highly fluid between  $850^{\circ}$  and  $1000^{\circ}$ . The result of this fluidity is that the test-pieces, on being taken out of the hardening bath, are only covered with a very thin coating of fused salt, sufficient to protect them from oxidation between the time of their withdrawal from the furnace and their immersion in the hardening bath, but insufficient to cause inequalities in surface hardening such as occur when a fused salt, at a temperature but little above its melting-point, is used.

As a matter of fact decarburisation is not entirely obviated if molten potassium chloride is employed alone. Thus a sample of steel containing 0.85 per cent. of carbon maintained for one hour in this salt at a temperature of  $1000^{\circ}$  showed, on micrographical examination, a carbide zone 0.6 millimetres in

thickness, the percentage of carbon decreasing towards the exterior to the extent of about 0.2 per cent. of carbon.

To avoid this disadvantage, there was added to the heating bath 2 per cent. of ferro-cyanide of potassium. It should, however, be noted that the period of heating the samples, except in the case of the special hardening of steels having high percentages of chromium and tungsten, never exceeded 20 to 25 minutes.

Surface oxidation was thus completely avoided, and the samples, after hardening and polishing with a wire brush, presented a brilliant and perfect surface without any of those traces of corrosion which are always to be observed, no matter what precautions may have been taken, after prolonged heating in an ordinary furnace, or where, on the other hand, the time of heating must be so short as to be absolutely incompatible with the development of complete and homogeneous quenching.

Quenching was carried out in water at an average temperature of 15°.

The whole of the samples forming part of a series of steels were heated and quenched together. With this object the following arrangement was fixed up: Over the end of an iron stem were threaded four sheet-iron discs kept from contact with one another by steel tubes cut to the requisite lengths. The two intermediate discs were drilled with a series of holes 8 millimetres in diameter, arranged in a circle, and through these holes were placed the steel test-bars, which were prevented from slipping about by the two end discs, which were unperforated. The perforated discs were threaded over the bar by square centre holes to prevent their turning, and the whole arrangement was tightened up by means of a bolt screwed on to the threaded extremity of the iron rod. The other end of the stem was provided with a handle which allowed of the samples being plunged into the bath. The whole appliance is illustrated in Fig. 43, which shows it in process of being used by a workman. During their stay in the bath the samples were constantly moved about so as to equalise the temperature of the molten salt. The temperature of the bath was ascertained by means of a Le Chatelier thermo-couple, protected by a fused quartz tube and placed



within a vertical iron tube closed at the bottom and immersed in the bath. The two wires of the thermo-couple were similarly insulated by small tubes of fused quartz. The thermo-couple was connected up with a Siemens-Halske



FIG. 43.—Appliance for placing Test-piece in the Hardening Bath.

galvanometer which may be seen on the left in Fig. 43, and was protected from the radiation of the furnace by an asbestos screen. The couple was standardised by the determination of the melting-points of antimony ( $630.6^{\circ}$  according to Holborn and Day), that of silver ( $962$  after Hasker), and of gold ( $1064^{\circ}$  according to Berthelot).



The furnace employed was of the Pernot form, which was modified by placing in the interior a cast-steel receiver furnished with a flanged bottom resting on the bottom of the furnace. This flange supported a refractory lining. The furnace is illustrated in the middle of Fig. 43. To the right may be seen the cylindrical hardening vessel.

#### 5. DURATION OF THE HEATING PREVIOUS TO HARDENING AND THE TEMPERATURE AT WHICH THE LATTER WAS EFFECTED.

The increase in the electrical resistance does not manifest itself until some of the carbon, or a carbide, has passed into solution owing to the heating, that is to say, when the temperature of the heating has exceeded the transformation point on cooling. Nevertheless it follows from the experiments made by H. Le Chatelier that it is not sufficient to exceed the critical temperature in order to obtain the maximum electrical resistance on quenching. Thus, with a steel containing 0.84 per cent.—that is to say, practically eutectic—he obtained the following results:—

Temperatures . . . . .	710°	740°	810°	850°	1000°
Resistance before quenching =	1.0	1.3	2.1	2.2	2.2
Resistance after quenching					

It will be seen that from 810° upwards the electrical resistance after quenching remains practically constant.

It is highly probable that in the samples employed in the experiments the whole of the cementite had disappeared, and that heating at a higher temperature could not therefore have led to an increase in the amount of dissolved carbon. The proportion of carbon dissolved is, further, a natural function of the duration of the steel at each temperature above the critical point as the solution of the carbon is not a sudden phenomenon, and the rate of dissolution varies with the temperature to which the steel is carried.

It is obvious that, from this point of view, the hardening of each type of steel necessitates a special investigation, and the author intends to undertake a series of experiments with this object, and in order to ascertain the influence of the tempera-

ture, and of the duration of heating previous to quenching, not only from the point of view of the solution of the carbon or the carbides, but also as regards the resulting influence on the mechanical and electrical properties of the hardened steels. But in the present instance the object is totally different as it is proposed to compare, from the point of view of electrical resistance, a series of steels, and to ascertain the relation which may exist between that resistance and their composition. It suffices, therefore, for this purpose, to carry out a strictly identical heat treatment on each class of steels, and to collate the results obtained. The sole condition requiring to be observed is obviously that of taking care that the temperature of quenching selected should be, in every case, about that of the highest transformation point of the series of steels under investigation. The researches of Osmond, Dumas, Böhrer, Arnold, and Madame Curie on the transformation points have been taken as a basis.

It was necessary, however, to undertake anew the determination of the critical temperatures of the vanadium steels—insufficiently investigated from this point of view—and those of the titanium steels.

## 6. MICROGRAPHICAL EXAMINATION.

Each series of determinations of the electrical resistance was supplemented by a micrographical examination carried out on one of the ends of the bars. The results obtained on the annealed steels do not differ appreciably from those published, in particular, by Osmond, Le Chatelier, Guillet, and Hadfield, and will only be referred to very briefly. Those found for the hardened steels are described in somewhat greater detail, without, however, unduly emphasising this particular aspect of the subject, which is but the corollary of the investigations in hand. Nevertheless it appeared to be of interest to place them on record, seeing that the conditions of heating and quenching were well defined, and differed from those dealt with in the researches already published on the subject.

The polished ends of the bars were examined by means of a

Le Chatelier microscope furnished with a special little arrangement for the purpose of conveniently observing specimens of relatively considerable length as compared with their thickness. Generally speaking, thanks to the extreme thinness of the samples, the structure is uniform throughout the section, and only on rare occasions were slight inequalities in hardening observed. Most of the structures observed having, in their broad aspects, been published in earlier investigations, it was deemed useless to crowd the present work with micrographs, and the author has therefore confined himself to enumerating the chief constituents encountered:—Pearlite, martensite, troostite, austenite, and double carbide.

### NICKEL STEELS.

Experiments were made on three series of steels, one containing 0.120 per cent. of carbon and the other about 0.250 per cent. Bars with a martensitic structure had to be machined on a grindstone. The analyses have been given on p. 240.

### HARDENING OF THE SAMPLES.

According to the investigations of Osmond and Dumas, nickel lowers the transformation points and subsequently raises the points of magnetic transformation up to a maximum at about 67 per cent. of nickel. In every instance a temperature of  $850^{\circ}$  is above all the highest transformation points of the nickel steels, but, with the object of obtaining martensite, even with steels having a low percentage of carbon and nickel, a tempering temperature of  $975^{\circ}$  was selected.

	Temperatures of Salt Bath. Degrees.			
Before the introduction of the samples . . .	.	.	.	995
After " " " . . .	.	.	.	915
Nine minutes after their immersion . . .	.	.	.	975

The period of immersion at  $975^{\circ}$  was 5 minutes, followed by quenching in water at  $15^{\circ}$ . In no instance were any cracks noticed in the hardened bars.

### VARIATION OF THE RESISTANCE WITH THE PERCENTAGE OF NICKEL.

1. *Steels containing 0·1 per Cent. of Carbon.*—The results are summarised in Table I. and the curves of Fig. 44.

Generally speaking, the resistance increases up to 10 per cent. of nickel, proceeding more slowly from 10 per cent. up to

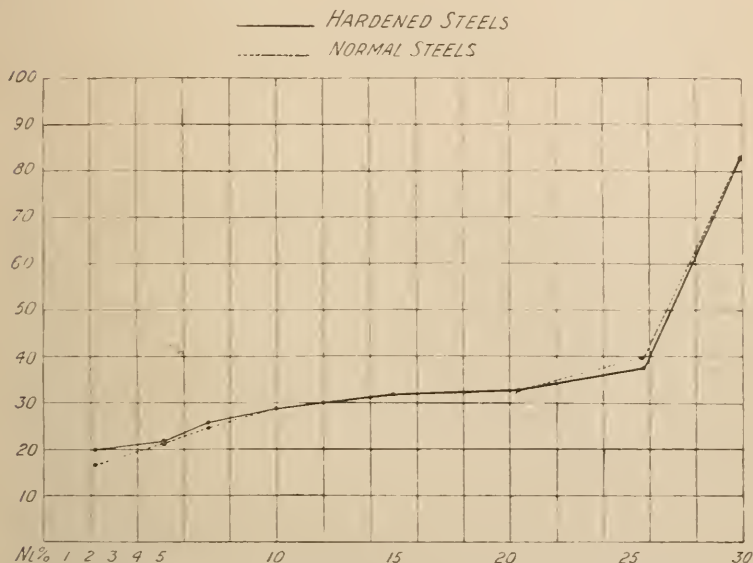


FIG. 44.—Nickel Steels containing 0·1 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

25 per cent. of nickel, and then undergoes a very rapid increase, starting from this percentage. The average values of the electrical resistance during these different stages are—

Nickel. Per Cent.	Rise in Resistance. Microhms.	Resistance for 1 per Cent. Ni. Microhms.
2 to 10	12·1	1·51
10 to 25	11·6	0·96
25 to 30	42·0	8·4

The atomic weight of nickel being 58.7, the specific increase in resistance due to the presence of each per cent. of nickel in solid solution in iron would be, according to Benedicks' formula—

$$26.8 \frac{12}{58.7} = 5.4 \text{ microhms.}$$

Benedicks' law is therefore inapplicable, at any rate to steels containing more than 2 per cent. of nickel. If the formula be applied, however, to steel 1Ni2, it will be found that, neglecting carbon and elements other than nickel, the electrical variation of the hardened steel would be—

$$7.6 + 26.8(0.07 + \frac{12}{28.4} 0.07 + \frac{12}{32} 0.006 + \frac{12}{55} 0.025) = 10.4 \text{ microhms.}$$

The increase in resistance due to 2 per cent. of nickel would thus be 9.6, or 4.8 for 1 per cent., a figure not far removed from that previously given. The limit to the applicability of Benedicks' formula is, therefore, 2 per cent. of nickel, or even less. If the influence of quenching be studied, it will be found that the three previously indicated groups behave in a slightly different manner.

*Group I.*—Hardening produces an increase in resistance (about 1.5 microhm).

TABLE I.

Description of Steel.	Carbon. Per Cent.	Nickel. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
1Ni2 . . .	0.07	2.23	16.6	20.0
1Ni5 . . .	0.12	5.23	22.2	22.4
1Ni7 . . .	0.12	7.13	24.9	25.8
1Ni10 . . .	0.13	10.10	28.7	28.6
1Ni12 . . .	0.12	12.07	30.1	30.1
1Ni15 . . .	0.11	15.17	32.8	32.5
1Ni20 . . .	0.18	20.40	33.5	33.3
1Ni25 . . .	0.16	25.85	40.3	37.8
1Ni30 . . .	0.12	30.00	82.4	82.4

*Group II.*—Hardening produces no variation in the electrical resistance.

*Group III.*—Hardening produces a slight diminution in the electrical resistance.

It should be noted that the latter fact was only observed in the case of steel 1Ni25. It may also be noted that the average increase of 1.5 microhm in the electrical resistance of the steels of Group I. on hardening corresponds to the passage into solution of about 0.05 per cent. of carbon.

2. *Steels containing 0.25 per Cent. of Carbon.*—

TABLE II.—*Temperatures, 20° and 21° (Curves of Fig. 45).*

Description of Steel.	Carbon. Per Cent.	Nickel. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
4N2 . . .	0.21	1.97	17.7	19.3
4N5 . . .	0.20	4.90	23.7	24.9
4N7 . . .	0.23	7.59	25.4	27.8
4N10 . . .	0.21	9.79	32.0	32.0
4N12 . . .	0.22	12.29	34.9	35.0
4N20 . . .	0.22	20.01	44.7	43.1
4N25 . . .	0.23	25.06	72.0	73.2
4N30 . . .	0.19	27.87	82.6	82.6

Here again three groups may be distinguished—

*Group I.*—2 to 7 per cent. of nickel. Quenching produces an increase in the electrical resistance which averages 1.7 microhms, and corresponds with the passage into solution of about 0.07 per cent. of carbon.

*Group II.*—7 to 20 per cent. of nickel. Quenching produces no variation in the electrical resistance.

In these two groups the increase in resistance with that in the percentage of nickel is practically constant, and may be estimated as, on an average, 27 microhms for 18 per cent. of nickel, or 1.5 microhms for each per cent. of nickel, a value nearly equal to that found in the first group, containing 0.1 per cent.

*Group III.*—20 to 30 per cent. of nickel. The specific resistance rises rapidly with the percentage of nickel to 37.9



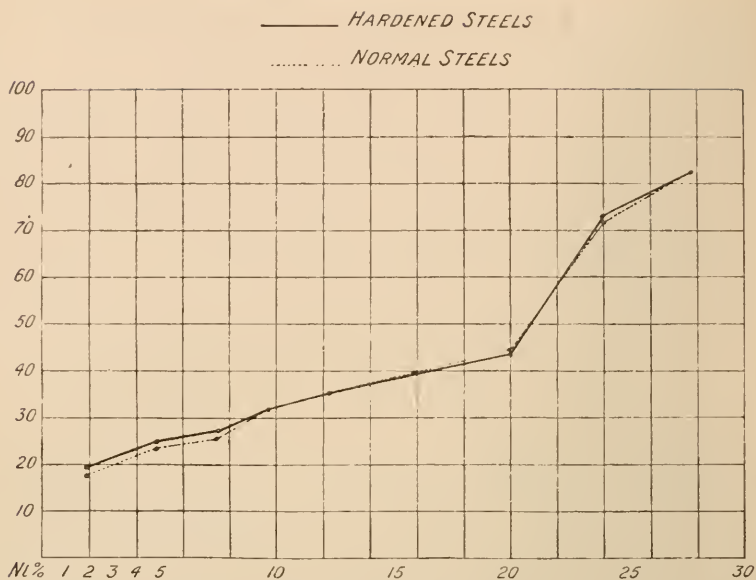


FIG. 45.—Nickel Steel containing 0.25 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

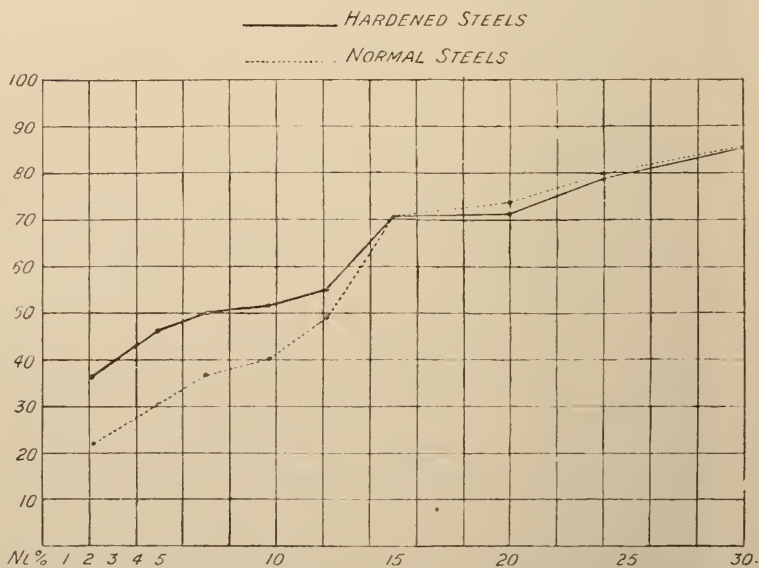


FIG. 46.—Nickel Steels containing 0.8 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

microhms for 7·8 per cent. of nickel, or 4·8 microhms for each per cent. of nickel. There may be observed, in some of the steels of this group, a diminution in the resistance on quenching.

3. *Steels containing 0·8 per Cent. of Carbon.*—

TABLE III.—*Temperature, 20° (Curves of Fig. 46).*

Description of Steel.	Carbon. Per Cent.	Nickel. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
9N2 . . . .	0·80	2·20	21·9	36·6
9N5 . . . .	0·78	4·90	31·4	46·2
9N7 . . . .	0·81	7·09	37·0	50·2
9N10 . . . .	1·05	9·79	40·2	51·7
9N12 . . . .	0·76	12·27	49·0	55·2
9N15 . . . .	0·80	15·04	71·0	70·6
9N20 . . . .	0·80	20·01	74·8	70·8
9N25 . . . .	0·79	25·06	80·4	79·1
9N30 . . . .	0·81	29·96	85·4	85·4

From 2 to 4 per cent. of nickel the difference between the electrical resistance of the hardened steels and that of the annealed steels is the same, and equals 14·75 microhms, a figure corresponding with 0·55 per cent. of hardening carbon. In these experiments, however, the temperature of quenching is higher than that of the critical points by only 350°. It appears difficult to deny that the whole of the available carbon has passed into solution. It must therefore be concluded that these steels, with about 0·8 per cent. of carbon, contain in the annealed state  $0·8 - 0·55 = 0·25$  per cent. of hardening carbon. This figure approximates closely to that found by Benedicks, who gives 0·27 per cent. of carbon as the coefficient of the solubility of carbon in iron at ordinary temperatures, and in presence of a certain excess of carbon.

From 7 to 15 per cent. the difference between the electrical resistance of the normal and hardened steels rapidly decreases from 13·2 to 0·4 microhms.

From 15 to 30 per cent. the specific electrical resistance of

the hardened steels remains slightly lower than that of the normal steels, with which it becomes identical at 30 per cent. of nickel. Within this range the increase in resistance in proportion to the percentage of nickel is small, being only 14.8 microhms for 15 per cent. of nickel, or 0.92 microhm for 1 per cent. of nickel.

If, in the case of the normal steel 9Ni2, the figure previously indicated for the dissolved carbon—0.25 per cent.—be taken, it will be found that the electrical resistance, ignoring the presence of the nickel, should be—

$$7.6 + 26.8 \left( 0.25 + 0.1 \frac{12}{28.4} + 0.005 \frac{12}{32} + 0.107 \frac{12}{55} \right) = 16 \text{ microhms.}$$

The presence of 2.2 per cent. of nickel in solid solution produces, therefore, an increase of 21.9 — 16.5 microhms, or 2.6 microhms for 1 per cent. of nickel, a figure substantially lower than the 5.4 microhms calculated from the atomic weight of nickel. 2 per cent. of nickel is, therefore, the upper limit of the applicability of Benedicks' formula to nickel in the case of steels containing 0.8 per cent. of carbon.

It may be remarked that the increase in the electrical resistance produced by the addition of nickel to steel may vary according to the percentage of carbon present. Nevertheless, in the three series examined, there is found nearly the same resistance, 82.4 to 85.4 microhms for a proportion of the element in the vicinity of 30 per cent. Another common point of agreement is that, with this percentage, hardening produces no effect on the electrical resistance.

#### RELATION BETWEEN THE SPECIFIC RESISTANCE AND THE MICROSTRUCTURE.

1. *Steels containing 0.1 per Cent. of Carbon.*—In the normal steels three classes were found, as shown by, in particular, Guillet—

	Nickel. Per Cent.	Structure.
1 . . .	0.0 to 10.0	Ferrite + pearlite.
2 . . .	10.0 to 27.0	Martensite.
3 . . .	over 27.0	Polyhedra of $\gamma$ -iron.

In the hardened steels, as has been shown, there may be

observed, after  $1\frac{1}{2}$  to 2 minutes' etching with Igewsky's reagent (alcoholic solution of picric acid), the following structures:—

*From 2 to 7 per Cent. of Nickel.*—Martensite and ferrite. The ferrite appears to occupy its original areas, and the martensite is found in the areas previously occupied by pearlite.

*7 per Cent. of Nickel.*—Martensite in which is still found a fine network revealing the former outlines of the ferrite grains, but the three dimensions characteristic of martensite are plainly visible.

*From 10 to 20 per Cent. of Nickel.*—Pure martensite, becoming coarser in proportion as the percentage of nickel rises.

*25 per Cent. of Nickel.*—Martensite and austenite appearing in coarse needles.

*30 per Cent. of Nickel.*—Polyhedral homogeneous crystals interspersed with a few lanceolated crystals, recalling the forms obtained by the sudden quenching of steels high in carbon.

If the foregoing results be considered together with those of the curve of the electrical resistance (Fig. 44) it may be said that—

(1) In the case of the pearlitic steels the resistance increases with the percentage of nickel, and further increases on hardening.

(2) In the martensitic steels the resistance increases slightly with the percentage of nickel, and is scarcely influenced by hardening.

(3) In the austenitic steels the electrical resistance increases rapidly up to 30 per cent. of nickel, but is slightly lowered by hardening.

2. *Steels containing 0.25 per Cent. of Carbon.*—The normal steels reveal, after etching with picric acid, the following microscopic appearances:—

	Nickel. Per Cent.	Structure.
1 . . .	0.0 to 7.0 . . .	Ferrite + pearlite.
2 . . .	7.0 to 26.0 . . .	Martensite.
3 . . .	over 25 . . .	Polyhedra of $\gamma$ -iron.

The hardened steels, after etching for 2 minutes with picric acid, are martensitic up to 20 per cent. of nickel. With 25 per

cent. of nickel polyhedra are observed, which become coloured brown by the action of the reagent, leaving a few lanceolated forms thrown into all the greater relief. At 30 per cent. of nickel a homogeneous polyhedral structure is obtained. If reference be made to the curve shown in Fig. 45 it will be seen that, as in the case of the steels containing 0·1 per cent. of carbon, hardening only produces an increase in the resistance of such steels as, in the normal state, reveal a pearlitic structure; the martensitic steels, on the other hand, remain, from the point of view of their electrical resistance, unaffected by quenching; while, in the same way, the polyhedral steels are distinguished by a very rapid increase in the electrical resistance, with an increase in the percentage of nickel, up to, at least, 30 per cent.

On the other hand, the increase in the electrical resistance as a function of the percentage of nickel is practically the same both for the pearlitic and for the austenitic steels.

3. *Steels containing 0·8 per Cent. of Carbon.*—In the normal state, steels containing 0·8 per cent. of carbon may be classified from the micrographic point of view, as follows:—

	Nickel. Per Cent.	Structure.
1 . . .	0·0 to 5·0 . . .	Ferrite + pearlite.
2 . . .	5·0 to 15·0 . . .	Martensite.
3 . . .	above 15 . . .	Polyhedra.

After hardening under the conditions already described, it will be observed that, after etching with picric acid (for about  $1\frac{1}{2}$  minute in the case of steels containing up to 15 per cent. of nickel, and about 3 minutes with steels containing over that percentage), the steels with 2 to 10 per cent. of nickel present a mixture of martensite and austenite; the latter constituent reveals itself either as lanceolated crystals or as white areas. The steel with 15 per cent. of nickel presents a transitional form in the sense that it consists of polyhedra, amongst which may still be detected some coarse needles of martensite. Above 15 per cent. of nickel (Fig. 64) the steels are distinctly polyhedral.

Here, again, the steels, which in their normal state are pearlitic, show a very notable increase in electrical resistance

on hardening. The martensitic steels also display an increase, which appears abnormal, but this increase becomes smaller as the percentage of nickel rises. It would thus appear that, as in the case of the preceding series of steels, the annealed martensitic steels containing all their carbon in the state of temper carbon, should not have their electrical resistance appreciably modified by hardening.

The polyhedral steels offer high resistances (70 to 80 microhms), and hardening appears rather to produce a slight lowering in this respect. This diminution of the electrical resistance of the polyhedral steels on hardening is always accompanied by the appearance of martensite in coarse needles, or in well-defined lanceolate forms, as is shown in the figure. This statement applies to the polyhedral steels in the neighbourhood of the martensitic steels.

To sum up: the influence of nickel reveals itself by an increase in the specific electrical resistance, which varies with the percentage of carbon and with the microstructure of the steel, high values being reached only with the polyhedral steels. Hardening only produces increased resistance in steels which, in the normal state, are pearlitic, and in those martensitic steels containing 0·8 per cent. of carbon. The passage from one structure to another is, generally speaking, increased by a change in the direction of the curve which represents the variations of specific resistance as a function of the percentage of nickel.

Benedicks' formula is not applicable for steel containing more than 2 per cent. of nickel.

### CHROMIUM STEELS.

Two series of chromium steels were investigated, the first containing about 0·2 per cent. of carbon, and the second 0·8 per cent. The complete analyses were given on p. 254. Nearly the whole of the test-pieces had to be trued on the grindstone. Certain specimens, such, in particular, as 8C12, having displayed inequalities in electrical resistance at various points along the length, were laid aside.



## HARDENING OF THE SAMPLES.

All the samples were quenched for a first time in water, after being heated in a salt bath. This first hardening is indicated in what follows by the letter A. A certain number of the samples underwent a second quenching, indicated by the letter B. This quenching was from a higher temperature, and after a considerably longer period of heating. The leading

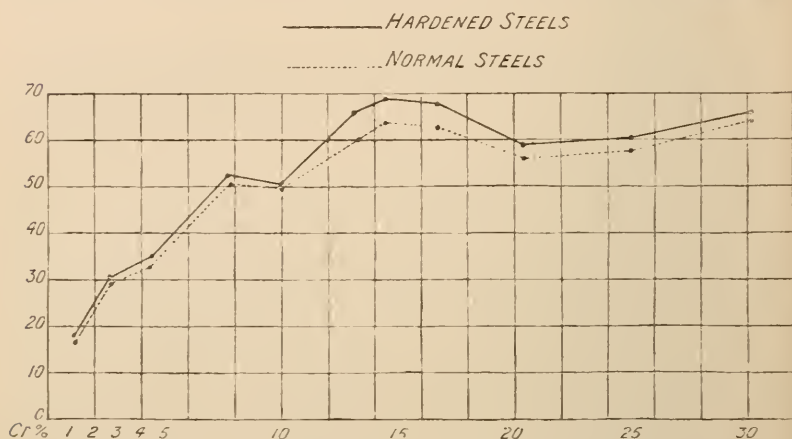


FIG. 47.—Chromium Steels containing 0·8 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

temperature distinctions of these two heat treatments were as follows:—

	Temperature of Bath.	
	A.	B.
Before introducing the test-pieces . . . . .	990°	1030°
After " " . . . . .	920°	950°
After " " . . . . .	980°	1020°
Duration of heating at the latter temperature, 980° .	5'	30'
Temperature of water bath . . . . .	12°	15°

Several of the samples cracked on quenching, in the direction of their length.

From the investigations of Osmond and of Madame Curie, chromium does not appear to act on the magnetic transformation point, but tends to raise the transformation

point  $A_1$ . The determinations published regarding this subject are, however, somewhat scanty, and do not relate to steels containing high percentages of chromium. The temperatures shown in the table below were therefore adopted somewhat arbitrarily.

# VARIATIONS OF THE RESISTANCE WITH THE PERCENTAGE OF CHROMIUM.

1. *Steels containing 0.2 per Cent. of Carbon.*—

TABLE IV.—*Temperatures, 12° and 17° (Fig. 47).*

Description of Steel.	Carbon. Per Cent.	Chromium. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Untreated. Per Cent.	Hardened (A). Per Cent.
1C1 . . . .	0.06	1.20	16.3	18.0
1C3 . . . .	0.28	2.66	29.7	31.0
1C5 . . . .	0.21	4.50	33.2	35.0
1C7 . . . .	0.07	7.84	50.9	53.0
1C10 . . . .	0.15	10.14	49.7	50.8
1C13 . . . .	0.17	13.36	60.0	66.6
1C15 . . . .	0.38	14.52	62.9	69.7
1C16 . . . .	0.15	16.71	64.7	68.1
1C20 . . . .	0.21	22.06	56.0	57.7
1C25 . . . .	0.24	25.31	57.5	60.2
1C30 . . . .	0.46	31.75	63.7	66.3

Up to 8 per cent. of chromium the resistance rises fairly regularly from 16.3 microhms to 50.9 microhms for the annealed steels, and from 18 microhms to 53 microhms for the hardened steels. This gives an average rise of about 36 microhms for an increased chromium percentage of 6.64 or 5.4 microhms for each per cent. of chromium. According to Benedicks' formula the increase in resistance due to each per cent. of chromium in solid solution in iron is—

$$26.8 \frac{12}{52.1} = 6.2 \text{ microhms,}$$

a figure not very far removed from the value found.

Further, if Benedicks' formula be applied in the case of the steel 1C3 (carbon, 0.28 per cent.; silicon, 0.05 per cent.;

manganese, 0.15 per cent.), assuming, with that observer, that a 0.28 per cent. steel contains on an average 0.13 per cent. of dissolved carbon, there is found, without taking into account the chromium present—

$$76 + 26.8 \left( 0.13 + \frac{0.05 \times 12}{28.4} + \frac{0.15 \times 12}{55} \right) = 12.5 \text{ microhms.}$$

The increased resistance due to the 2.67 per cent. of chromium contained in this steel is, therefore, 17.2 microhms, or 6.4 for 1 per cent. of chromium. The formula is thus applicable up to this amount. The resistance continues to increase up

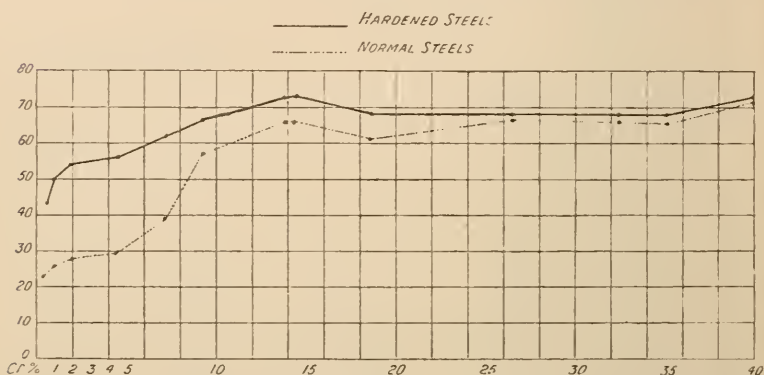


FIG. 48.—Chromium Steels containing 0.8 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

to about 13 per cent. of chromium. But if the irregularities of the curve are taken into account, it is possible to distinguish three portions, which may each be distinguished by their average increase in electrical resistance; that is to say, by the angular co-efficient of the chord of the intervening portion of the curve.

	Chromium, Per Cent.	Inc. ease in Resistance, (Hardened Steels.) Microhms.	Average Increase in Resistance (for 1 per Cent. of Chromium).
1	1 to 8	36	5.4
2	8 to 14	16.7	2.7
3	14 to 30	2.6	-0.15

In any case, what was very clearly brought out was the change in the general nature of the curve above 14 per cent. of chromium. The resistance, which steadily increased for percentages below 14, became practically constant once this proportion of chromium was exceeded.

The increase in the electrical resistance on hardening occurred in all the steels, and seemed greater in steels containing high percentages of chromium than in the case of steels containing low percentages of that element. It is, however, necessary to point out that in the latter steels the proportion of carbon is relatively lower.

2. *Steels containing 0·8 per cent. of Carbon.*—

TABLE V.—*Temperatures, 20° and 15° (Curves of Fig. 48).*

Description of Steel.	Carbon. Per Cent.	Chromium. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Untreated. Per Cent.	Hardened (A). Per Cent.
8C0·5 . . . .	0·86	0·62	23·1	43·5
8C1 . . . .	0·97	0·99	25·8	50·2
8C2 . . . .	0·89	2·14	27·8	54·0
8C5 . . . .	0·79	4·57	29·4	56·3
8C7 . . . .	0·84	7·28	39·1	62·2
8C10 . . . .	0·75	9·38	56·4	66·5
8C16 . . . .	0·70	13·94	65·4	72·5
8C15 . . . .	0·74	14·54	66·2	73·1
8C20 . . . .	0·90	18·65	60·7	68·3
8C25 . . . .	0·82	26·54	67·1	68·4
8C30 . . . .	0·92	32·46	66·3	67·5
8C35 . . . .	0·83	36·34	65·1	68·5
8C40 . . . .	0·80	40·03	71·5	73·5

With the normal steels the resistance increases rapidly enough up to 9 per cent. of chromium, and subsequently increases slowly up to 40 per cent., as is clearly brought out by the following figures:—

	Chromium. Per Cent.	Microhms.
Increase in resistance from . . . . . or 3 to 8 microhms for each per cent. of chromium.	0·62 to 9·38	33·3
Increase in resistance from . . . . . or 0·5 microhm for each per cent. of chromium.	9·38 to 40	15

In the hardened steels the resistance undergoes a sudden

increase up to 2 per cent. of chromium, and then increases slowly up to 14 per cent., after which it remains nearly constant.

This difference in the behaviour of the two curves allows of these steels being distinctively ranged into three groups, distinguished by the amount of increased electrical resistance produced by hardening.

Class of Steel.		Increased Resistance on Hardening.			Mean Value of the Resistance on Hardening in Terms of Hardening Carbon. Per Cent.
Group.	Chromium. Per Cent.	Maximum. Per Cent.	Minimum. Per Cent.	Average. Per Cent.	
I.	0·06 to 7·0	26·9	20·4	24·2	0·9
II.	9·0 to 18·0	10·1	7·1	8·1	0·3
III.	26·0 to 40·0	3·4	1·2	1·9	0·07

In the last columns of the foregoing tables have been added the amounts of carbon which, when passed into solid solution, would produce an increase in resistance equivalent to the average increase produced in each group by hardening. It may be noted that, in the case of steels containing 0·6 to 7 per cent. of chromium, this value for the hardening carbon is equal to an average percentage of 0·9 of carbon in those steels. The low percentages of chromium appear, therefore, either to facilitate the passage of the hardening carbon into solid solution, or to cause a simultaneous dissolution of chromium and of carbide. On the other hand, in the case of high chromium percentages, the increase in resistance on hardening is insignificant, although this might be similarly due to an insufficiently high hardening temperature, or to too short a period of heating.

#### RELATION BETWEEN THE SPECIFIC RESISTANCE AND THE MICROSTRUCTURE.

1. *Steels containing 0·2 per Cent. of Carbon.*—The microstructure of the reheated steels allows of their being classified in the manner shown by Guillet, as follows:—

	Chromium. Per Cent.	Nature of Steels.
1	0·0 to 7·0	Pearlitic steels.
2	7·0 to 20·0	Martensitic steels.
	7·0 to 8·0	Ferrite and martensite.
	8·0 to 13·0	Pure martensite.
	13·0 to 20·0	Martensite and double carbide of iron and chromium.
3	Steels with over 20·0	Double carbide.

With regard to the hardened steels, as has been shown above (Treatment A), the micrographic examination can be summed up, on broad lines, as follows:—

(1) Up to 14 per cent. of chromium the steels display a martensitic structure coloured with difficulty and showing, in the case of the steel containing 13·36 per cent. of chromium, dark lines which appear to consist of troostite. From 14·52 per cent. of chromium, upwards, the white points of the double carbide of chromium and iron appear in relief, as well as black filaments presenting at times the appearance of a network often enclosing the grains of carbide. This is probably troostite, which appears to indicate the areas in which the carbide has begun to dissolve owing to the heating previous to hardening. These steels are only etched with great difficulty, and when the percentage of chromium does not exceed 9·0 a solution of potassium bisulphate and of hydrochloric acid is usually employed. Even then the etching is often very slow and the result often indistinct. It is preferable to develop the microstructures—and this statement appears to apply generally to all steels containing the double carbide—by means of a sulpho-chromic solution containing:—

Sulphuric acid	.	.	.	.	25 cubic centimetres.
Chromic acid	.	.	.	.	2 grammes.
Water	.	.	.	.	75 cubic centimetres.

The temperature and length of attack vary with the percentage of chromium. Thus, in the case of steels containing up to 5 per cent. of chromium, an attack of 20 to 30 seconds suffices; for those containing 7 to 20 per cent. of chromium at least 30 seconds are required at 40° C., while steels containing 25 per cent. of chromium or more require 3 to 4 minutes at boiling-point. The degree of etching may, however, be very



well gauged by observing the evolution of gas from the surface acted upon.

The first fact which reveals itself on comparing the microstructure with the curve showing the electrical resistance (Fig. 48) is that the presence of the double carbide corresponds with a constant degree of resistance, or with one that diminishes in proportion to the increase in the percentage of chromium. The curve of the resistance affords, therefore, a means of ascertaining the limit of solubility of the double carbide of iron and chromium in the solid state. It should be noted that quenching from a higher temperature (Treatment B), carried out on a steel containing 22 per cent. of chromium, does not occasion any increase in the electrical resistance. It should also be noted that the rapid increase in electrical resistance with the increase in the percentage of chromium (5.4 microhms for each per cent. of chromium) which occurs in the case of low percentages of chromium, extends over the whole range of the pearlitic steels. The appearance of martensite in the normal steels seems to reveal itself, as in the case of the nickel steels, by a lower degree of increased electrical resistance.

2. *Steels containing 0.8 per Cent. of Carbon.*—In the case of the normal steels Guillet has shown the following classification to obtain:—

Group.	Chromium. Per Cent.	Microstructure.
I. . . . .	0.0 to 5.0 . . . . .	Pearlitic steels.
II. . . . .	5.0 to 18.0 . . . . .	Martensitic steels.
III. . . . .	over 18.0 . . . . .	Double carbide steels.

By etching the hardened steels with the sulpho-chromic reagent already referred to (Treatment A), it was clearly found that the double carbide of iron and chromium begins to appear at 9 per cent. of chromium. Below this percentage a homogeneous martensite occurs, which is finer and finer in texture in proportion as the percentage of chromium decreases. Further, it was ascertained that troostite always occurs once 18 per cent. of chromium is exceeded (Fig. 65). It often presents the appearance of a black nodular network surrounding the white grains of the double carbide. If these results

be compared with those obtained in studying the electrical resistance, the following conclusions may be drawn as regards chromium steels containing about 0·8 per cent. of carbon:—

(1) The steels which, in the normal condition, contain pearlite undergo a considerable increase in electrical resistance on hardening (about 24·2 microhms).

(2) The steels which, in the normal state, are martensitic undergo, on hardening, an increased electrical resistance one-third as great as the former class.

(3) Steels containing the double carbide undergo only a very slight increase in electrical resistance on hardening (1·9 microhm, on the average, in the case of the steel under investigation).

(4) The appearance of the double carbide in the series of hardened steels reveals itself by a more constant degree of resistance in respect to the percentage of chromium.\*

It should be clearly understood that these results are in no way absolute; the limits of the changes in microstructure and in electrical resistance indicated being but approximate, owing to the gaps which existed in the series of steels studied. They appear, however, fairly coherent inasmuch as, on the one hand, hardening has the effect, with the pearlitic steels, of making the carbon pass into the condition of solid solution, whereas previously it existed, in an undissolved state, in the cementite, and, on the other hand, the appearance, in the series of steels containing a constant percentage of carbon, of a constituent, the double carbide, tends to reduce to a straight line the curve of the electrical resistance and likewise to deprive the solid solution surrounding the carbide, of its carbon.

Hardening experiments at higher temperatures (Treatment B) were carried out on the steels 8Cr10, 8Cr15, and 8Cr20 without the proportion of double carbide being perceptibly diminished, while the electrical resistance underwent no change of any importance, except in the case of steel 8Cr20,

\* It should not, however, be forgotten in this connection that, even if the material investigated always consisted of a solid solution of iron-chromium (with a constant percentage of carbon, but an increasing percentage of chromium), the angular co-efficient of the tangent to the curve of the resistance would tend to approach 0° in proportion as the percentage of chromium increased.

but as this steel cracked on quenching it was not found possible accurately to establish the amount of the increased electrical resistance it underwent.

### TUNGSTEN STEELS.

Two series of steels, containing respectively 0.25 and 0.8 per cent. of carbon, were examined. The bars employed presented, in respect of their length, a satisfactory degree of

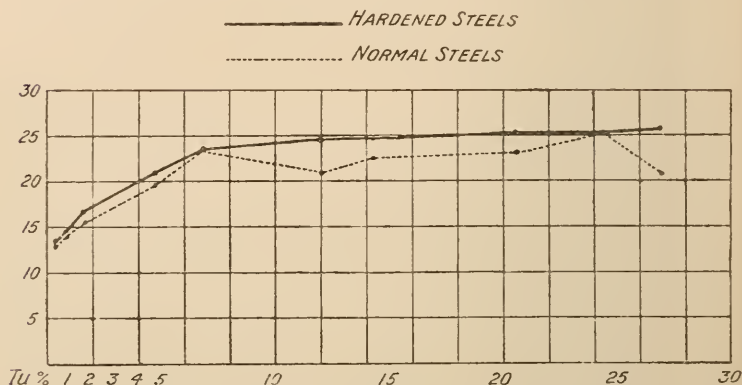


FIG. 49.—Tungsten Steels containing 0.2 per cent. of Carbon. Electrical Resistance in microhms per cubic centimetre.

homogeneity, from the point of view of electrical resistance. The complete analyses are given on p. 260.

The influence of tungsten on the electrical resistance of steel has already been investigated by Barrett, Brown, and Hadfield, who examined steels containing up to 40 per cent. of tungsten.

### HARDENING OF THE SAMPLES.

According to the determinations made by Osmond and by Otto Böhler, tungsten tends to raise the transformation points and the position of the critical points varies, as in chromium steels with the cycle of previous temperature conditions, and with the rate of cooling. The rise in the transformation

points is not large. Thus, a steel containing 0·85 per cent. of carbon and 7·78 per cent. of tungsten, studied by Böhler, gave an upper critical temperature at 710°. The temperature of hardening adopted in the present experiments was, however, 1000°, and the heat treatment was as follows:—

	Temperature of the Heating Bath, Degrees.
Before introducing the test-pieces . . . . .	1000
After       "       "       "       "       "       " . . . . .	915
After 10 minutes' heating . . . . .	975
" 15   "   "   "   "   "   "   "   "   " . . . . .	1000

The temperature of the hardening bath was 20°.

### VARIATION OF THE RESISTANCE WITH THE PERCENTAGE OF TUNGSTEN.

#### 1. Steels containing 0·2 per Cent. of Carbon.—

TABLE VI.—*Temperatures, 15° and 20° (Curves of Fig. 49).*

Description of Steel.	Carbon. Per Cent.	Tungsten. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Quenched Steels. Per Cent.
1T0·5 . . . .	0·12	0·41	12·8	13·8
1T1 . . . .	0·11	0·93	13·5	14·3
1T2 . . . .	0·11	1·75	15·8	17·1
1T5 . . . .	0·13	4·96	19·5	21·1
1T7 . . . .	0·13	6·90	23·3	23·4
1T10 . . . .	0·17	11·89	20·9	24·5
1T15 . . . .	0·20	14·37	22·6	24·6
1T20 . . . .	0·22	20·71	23·1	25·3
1T25 . . . .	0·22	24·35	25·3	25·2
1T30 . . . .	0·28	27·05	20·7	25·8

The electrical resistance increases up to 11 per cent. of tungsten. From 11 per cent. upwards it is nearly constant. The increase in the resistance—from 0·4 to 6·9 per cent. of tungsten is, in the case of the hardened steels, 9·6 microhms, or about 1·5 microhm for 1 per cent. of tungsten. From 11·89 to 27·05 per cent. of tungsten it is 2·4 microhms, or about 0·16 for 1 per cent. of tungsten. According to

Benedicks' formula there would be obtained, as the resistance due to the presence of tungsten in solid solution in iron:—

$$26.8 \times \frac{12}{184} = 1.7 \text{ microhm.}$$

The formula is approximately constant, therefore, up to 7 per cent. of tungsten, and, in any case the tungsten is in solid solution in the iron up to, at least, this percentage.

Quenching produces an increase in the resistance, but the curve relating to the normal steels presents irregularities due to the inequalities in annealing, whereas the curve which relates to the hardened steels presents perfect regularity.

2. *Steels containing 0.8 per Cent. of Carbon.*—

TABLE VII.—*Temperatures, 15° and 20° (Curves of Fig. 50).*

Description of Steel.	Carbon. Per Cent.	Tungsten. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
8T0.5 . . .	0.86	0.40	22.4	39.1
8T1 . . .	0.66	0.95	20.9	39.6
8T2 . . .	0.79	2.75	24.3	40.9
8T5 . . .	0.33	4.68	28.1	41.2
8T10 . . .	0.81	9.99	26.9	39.5
8T15 . . .	0.71	14.75	26.5	32.3
8T20 . . .	0.74	19.25	25.3	31.0

With the annealed steels the electrical resistance increases up to about 5 per cent. of tungsten to fall subsequently, with the exception of the first steel 8T0.5, which seems to be not within the general character of the curve. It is found that with 0.95 to 4.68 per cent. of tungsten the increase is 7.2 microhms, or 1.7 for each per cent. of tungsten. This figure agrees with that calculated from Benedicks' formula, and it may be granted that, up to, at least, 5 per cent., the tungsten is in solid solution in the iron.

Above 4.68 per cent. of tungsten the electrical resistance begins to decrease, and the fall is 0.17 microhm for each per cent. of tungsten.

In the hardened steels the increase in the resistance up to about 5 per cent. is much less than it is in the annealed steels, but this arises from the difference in the percentage of carbon in these steels. After this point the resistance decreases somewhat rapidly, particularly between 10 and 15 per cent. of tungsten (1·5 microhm for each per cent. of tungsten).

The increase in electrical resistance on quenching, particularly in the case of steels containing up to 10 per cent. of tungsten (an increased resistance of about 15·5 microhms)

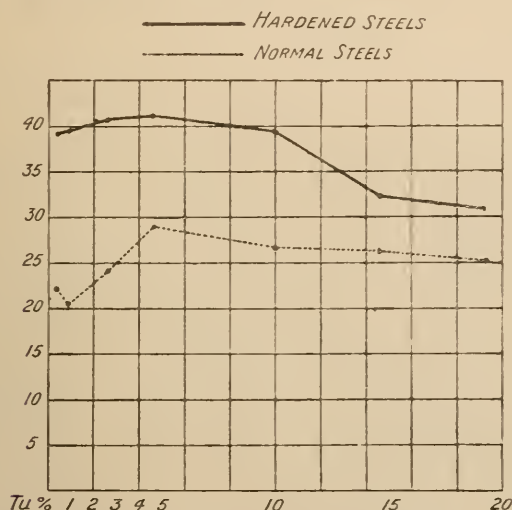


FIG. 50.—Tungsten Steels containing 0·8 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

becomes subsequently much smaller (5·7 microhms). It would appear, therefore, that the presence of relatively large quantities of tungsten in a steel diminishes the solubility of the carbon during the heating which precedes the quenching.

#### RELATION BETWEEN THE SPECIFIC RESISTANCE AND THE MICROSTRUCTURE.

1. *Steels containing 0·2 per Cent. of Carbon.*—The normal steels may be divided into two groups:—

- |          |                             |                        |
|----------|-----------------------------|------------------------|
| Group I. | Tungsten under 10 per cent. | Pearlitic steels.      |
| „ II.    | „ over „                    | Double carbide steels. |



Quenching, in the manner in which it was effected, conduces to the solution of the double carbide except in steels with high percentages of tungsten, so that these steels may be classified as follows.\*—

*Group I.*—Containing up to 25 per cent. of tungsten. Martensitic steels. This martensite is always accompanied by troostite, particularly in steels which, previous to quenching, contain the double carbide of iron and tungsten.

*Group II.*—25 per cent. of tungsten and upwards. Steels containing the double carbide and martensite, and sometimes a black network of troostite.

It would thus seem that in the normal steels the appearance of the double carbide stops the somewhat notable increase of the resistance with a rise in the percentage of tungsten which is observed in the case of steels containing less than 10 per cent. of tungsten and that, further, the solution of the double carbide is accompanied by a fairly noteworthy increase in the electrical resistance, as in the steels containing 10 to 25 per cent. of tungsten. There may be seen a difference in the electrical resistance of the steels before and after quenching, which amounts to about 2·5 microhms.

2. *Steels containing 0·8 per Cent. of Carbon.*—The microscopic examination of the normal steels allows of the following classification being made:—

Group I.	Tungsten, 0·0 to 5·0 per cent.	Pearlitic steels.
„ II.	Above 5·0 . . . . .	Double carbide steels.

In the case of the hardened steels a slight diminution in the amount of double carbide may be observed in those which contain it, together with the appearance of a martensitic structure, which becomes strongly coloured on etching with picric acid.

It may be seen very clearly that the resistance of the normal steels increases very rapidly with the percentage of tungsten as long as the steel does not contain any double carbide, and then decreases. This decrease in the electrical

\* Etching was effected by means of picric acid. For high percentages of tungsten (above 20 per cent.) picric acid and the sulpho-chromic mixture previously described were employed for comparison.

resistance of steels containing the double carbide is particularly marked in the hardened steels, so that the increase in the resistance on hardening becomes smaller as the percentage of tungsten increases. It seems to follow that in the double carbide steels, tungsten hinders the solution of carbon on quenching.

It may be seen, therefore, that in the case of the tungsten steels the law as to the variation in the electrical resistance as a function of the percentage of tungsten present depends upon the microstructure of the steel, and, in particular, that in the case of the normal steels containing 0·8 per cent. of carbon the appearance of the double carbide which marks the termination of the complete solution of the tungsten in the iron, in the presence of carbon indicates, at the same time, the limit of applicability of Benedicks' formula to these steels.

Hardening tests at a higher temperature ( $1030^{\circ}$ ) and after prolonged heating (half-an-hour) were carried out on the steels shown in Tables VI. and VII. by 1T10; 1T20; 8T10; and 8T20. They failed to establish any increase in the resistance in the case of the samples containing 0·8 per cent. of carbon, which, on the other hand, still reveal, under the microscope, spots of double carbide. In the case of those containing 0·2 per cent. of carbon there was noticed, in respect of the first hardening, a lowering of the troostite, and a slight increase in the electrical resistance (on an average, 1·0 microhm).

### ALUMINIUM STEELS.

The investigations were conducted on two series, one containing, on an average, about 0·13 per cent. of carbon, and the other about 0·75 per cent. In the first series, the aluminium rises until it reaches 7 per cent., and in the other until it reaches 15 per cent. The complete analyses are shown on p. 265.

### HARDENING OF THE SAMPLES.

The samples were hardened in the same way as the nickel steels, that is to say, in air, from  $975^{\circ}$ , after remaining for

4 minutes at that temperature and 15 minutes altogether in the salt bath.

With regard to the transformation points of the aluminium steels, the following somewhat contradictory facts have been ascertained. Osmond, noticing that the cooling curve of a steel studied by Hadfield, and containing 5 per cent. of aluminium but no carbon, did not show the point  $Ar_3$ , concluded that aluminium keeps the iron, at least in part, and at ordinary temperatures, in the same state as at the fusion point. On the other hand, Gwyer, in his researches on aluminium-iron-alloys, found that the magnetic transformation point was lowered by the addition of aluminium. The thermal effects which accompany the phenomenon have been ascertained up to 20 per cent. of aluminium, and on the other hand, given the same conditions, the evolution of heat which marks the transformation of  $\alpha$ -iron into  $\beta$ -iron is no longer perceptible from 1 per cent. of aluminium per cent.

#### VARIATION OF THE ELECTRICAL RESISTANCE WITH THE PERCENTAGE OF ALUMINIUM.

##### 1. Steels containing 0·13 per Cent. of Carbon.—

TABLE VIII.—Temperatures, 23° and 20°.

Description of Steel.	Carbon. Per Cent.	Aluminium. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
1A0·5 . . .	0·09	0·51	17·1	17·5
1A1 . . . .	0·11	1·08	26·3	27·2
1A2 . . . .	0·17	2·04	35·9	35·5
1A3 . . . .	0·13	3·05	50·7	51·4
1A5 . . . .	0·17	5·08	63·6	65·4
1A7 . . . .	0·08	7·18	76·6	77·3

Aluminium produces a very rapid increase in the electrical resistance. It is necessary to note, on the other hand, the

slight influence of quenching on the resistance of these steels. Indeed, for this series, the average increase in resistance on quenching is only 0.68 microhm, which corresponds with the passage into solution of 0.026 per cent. of carbon. Although in Fig. 51 it was necessary to exaggerate graphically the difference between the two curves, as unless this were done it would not be possible to distinguish it for a certain portion of their length, it will be seen in what follows that they practically resemble each other, and it will only be necessary to deal with the curve of resistance relative to the hardened steels containing 0.13 per cent. of carbon.

This curve is fairly regular, and presents but a slight curvature. It differs, nevertheless, from a straight line, besides which the results of Table VIII. may be approximately expressed by means of the empirical formula—

$$\rho = 12 + 12x - 0.3x^2$$

in which  $\rho$  is the resistance and  $x$  the percentage of aluminium in the steel. It may be noted that, if  $x$  be taken as equal to 0,  $\rho$  will be equal to 12, which is practically the resistance of a steel containing 0.13 per cent. of dissolved carbon, and a percentage of other impurities equal to the average amount of such impurities in the steels of this series.

The angular co-efficient of the tangent of this parabola is—

$$\frac{d\rho}{dx} = 12 - 0.6x$$

when

$$x = \text{nil} : \left. \frac{d\rho}{dx} \right|_{x=0} = 12,$$

a figure corresponding closely with that obtained by assuming the equality of the electrical resistance of solid solutions of equi-atomic iron. As a matter of fact,  $26.8 \frac{12}{27.1} = 11.9$  microhms for each percentage of aluminium. Benedicks' linear formula is in this case the equation of the tangent at the starting-point of the curve.

Benedicks' formula applies accurately between 0.0 and 1 per cent. of aluminium, as the average value of the variation in resistance within this interval is—

$$\rho_1 - \rho_0 = 11.7.$$

## 2. Steels containing 0.75 per Cent. of Carbon.—

TABLE IX.—Temperatures, 23° and 19° (Curves of Fig. 52).

Description of Steel.	Carbon, Per Cent.	Aluminium, Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels, Per Cent.	Hardened Steels, Per Cent.
SA1 . . . .	0.67	1.05	30.3	41.8
SA2 . . . .	0.80	2.09	47.4	57.2
SA3 . . . .	0.69	2.89	53.0	60.9
SA5 . . . .	0.81	4.65	65.6	76.5
SA10 . . . .	0.66	9.15	92.6	100.6
SA15 . . . .	0.87	14.90	87.8	99.6

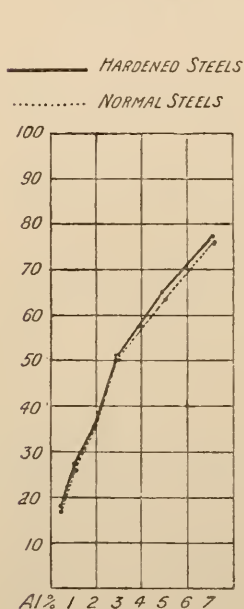


FIG. 51.—Aluminium Steels containing 0.2 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

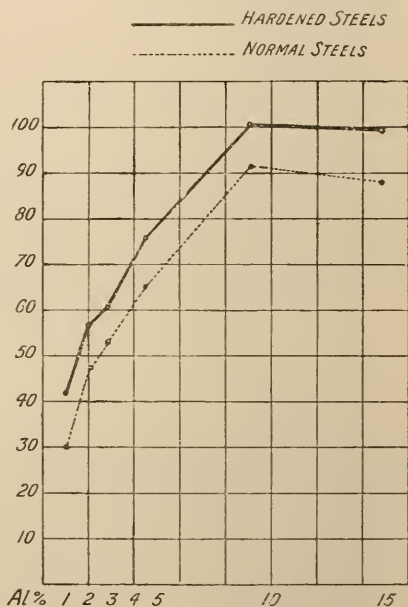


FIG. 52.—Aluminium Steels containing 0.8 per cent. of Carbon. Electrical resistance in microhms per cubic centimetre.

Up to the steel containing 9.15 per cent. of aluminium, the electrical resistance increases rapidly enough, both in the case

of the normal steels and in that of the hardened steels. Proceeding to the steel containing 14.9 per cent. of aluminium, a resistance practically the same as in the steel with 9.15 per cent. is found in the case of the hardened steel, and a slight decrease in the normal steels.

If the normal steels belonging to this series be compared with the hardened steels of the preceding series, it will be seen that the two curves which represent the resistances as functions of the percentages of aluminium are very nearly parallel, and, vertically, 3.7 microhms apart. Up to 10 per cent. of aluminium the electrical resistance of the normal steels containing 0.75 per cent. of carbon may be expressed by the formula—

$$\rho = 15.7 + 12x - 0.3x^2.$$

This figure, 3.7 microhms, represents the increase in electrical resistance due to the presence of 0.14 per cent. of carbon in solid solution. Now, the hardened steels of the preceding series contained, on an average, 0.3 per cent. of dissolved carbon. It must be admitted, therefore, that the normal steels with 0.75 per cent. of carbon contain 0.27 per cent. of the carbon in solid solution. This agrees with the determinations of Benedicks in the case of ordinary carbon steels.

Up to 10 per cent. of aluminium the variation of the resistance of the hardened steels containing 0.75 per cent. of carbon may similarly be represented by the formula—

$$\rho = 28.2 + 12.9x - 0.56x^2.$$

These formulæ have, of course, no absolute value. They were drawn up so as to combine the average minimum difference between the figures found by experiment and those calculated from formulæ. They possess the advantage of giving the general idea of the influence conferred by aluminium and by hardening on the electrical resistance, apart from the secondary variations due to the presence of impurities or to experimental errors.



RELATION BETWEEN THE SPECIFIC RESISTANCE AND  
THE MICROSTRUCTURE.

1. *Steels containing 0.1 per Cent. of Carbon.*—All the steels of this series are pearlitic in the normal condition, and hardening has only the effect of substituting martensite for the previous pearlite. The aluminium enters into solution in the iron,\* and, on the one hand, isolates the pearlite in the annealed steels into masses having a granular shape; and, on the other hand, is incapable of taking up carbon, in solid solution, on hardening.

This explains, in the first place, the great increase in the electrical resistance with the increase in the percentage of aluminium, an increase resulting from the presence, in solid solution in the iron, of increasing increments of an element having a low atomic weight. It also explains the small change undergone by the resistance, on hardening.

2. *Steels containing 0.8 per Cent. of Carbon.*—Up to 10 per cent. of aluminium the structure of the normal steels is pearlitic. Above this percentage there appears a special constituent which, according to Guillet, is cementite. With regard to the hardened steels, they show martensite in lieu of pearlite. The appearance of the special constituent is accompanied by a change in the direction of the curve of the electrical resistance, which, up to 10 per cent. of aluminium, rises rapidly, as in the steels of Series I. Here, again, the variations in the electrical resistance are, in a general way, connected with the structure of the steel.

## MOLYBDENUM STEELS.

Only seven samples of molybdenum steels could be investigated, as those containing 0.2 per cent. of carbon cannot be forged when the proportion of molybdenum reaches 10 per cent., and those containing 0.8 per cent. of carbon cannot be forged when the proportion of molybdenum reaches 5 per cent.

\* The limit of solubility in the solid state for aluminium in iron, in the absence of carbon, was found to be 34 per cent. See Gwyer, *Zeitschrift für Anorganische Chemie*, vol. lvii, p. 126.

Few results respecting the influence of molybdenum on the transformation points are available. The experiments carried out by Madame Curie lead to the belief that the critical temperatures of the steels investigated in the course of the present research do not differ greatly from those of the binary steels containing similar percentages of carbon. The steels were hardened at  $950^{\circ}$ , as in the case of the aluminium steels.

The results of the determinations of the electrical resistance are shown in the following table, and the analyses are given on p. 274.

TABLE X.—*Molybdenum Steels. Temperatures,  $17^{\circ}$  and  $19^{\circ}$ .*

Description of Steel.	Carbon. Per Cent.	Molybdenum. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
2Mo0.5 . . .	0.19	0.45	16.2	17.8
2Mo1 . . .	0.16	1.00	16.5	17.1
2Mo2 . . .	0.14	2.20	18.2	20.0
2Mo5 . . .	0.29	4.50	30.2	31.8
8Mc0.5 . . .	0.74	0.50	18.1	37.6
8Mo1 . . .	0.81	1.21	23.4	39.5
8Mo2 . . .	0.81	1.98	25.6	40.7

It was deemed unnecessary to compile curves, as the range of the percentages of molybdenum was too restricted.

The increase in the electrical resistance in the case of the normal steels containing 0.2 per cent. of carbon was 14 microhms, when the percentage of molybdenum rises from 0.45 to 4.5, which gives an average of 3.4 microhms for each per cent. of molybdenum. This figure is the same as that obtained by calculations based on the atomic weight of molybdenum,  $3.4 = 26.8 \frac{12}{96}$ . It may therefore be concluded that, up to 5 per cent., the molybdenum is in solid solution in the iron. Also, it is from 5 per cent. upwards that, as is shown by micrographical methods, the double carbide of molybdenum and iron commences to appear.

If the same calculation be made in respect of the steels of the second series, there will be found, as the average value of the increased electrical resistance due to the increasing percentage of molybdenum :—

$$\frac{25.6 - 18.1}{1.98 - 0.50} = 5 \text{ microhms for each per cent. of molybdenum.}$$

This figure is markedly higher than the preceding, and it must therefore be concluded that, in the case of steels containing 0.8 per cent. of carbon, increasing increments of carbon pass into solid solution as the percentage of molybdenum rises. This assumption would also appear to be borne out by the variations in the increase of resistance on quenching, shown in the following table :—

Percentage of Molybdenum.	Increase in Resistance on Hardening. Per Cent.	Amount of Carbon in Solid Solution, Corresponding to this Increase. Per Cent.
0.50	19.5	0.73
1.20	16.1	0.60
1.98	15.1	0.56

On the other hand, the appearance of the double carbide seems to impose a limit to the increase in electrical resistance of the hardened steels observed to occur with increasing proportions of manganese (?). Indeed, the electrical resistance of the hardened steels containing 0.8 per cent. increases by 2.7 microhms for each per cent. of molybdenum when the proportion of molybdenum rises from 0.5 to 1.21 per cent., and by 1.5 microhm for each per cent. of molybdenum when the proportion of that element is comprised between the limits of 1.21 and 1.98 per cent. The micrography of the steel containing 1.98 per cent. of molybdenum reveals, moreover, on hardening at 950°, small but very distinct grains of double carbide, after an etching carried out with the sulpho-chromic mixture.

It is not possible, however, in regard to these steels, to do more than to place on record a few of the observances, as the

number studied was too small, and the steels corresponded with too small a range of molybdenum.

### VANADIUM STEELS.

The two series of steels investigated contained respectively about 0·2 per cent. of carbon, and percentages of vanadium varying from 0·6 to 7·0, and 0·8 per cent. of carbon, with vanadium ranging from 0·25 to 10 per cent. The analyses are given in the table below.

With the object of determining the hardening temperature, a complete investigation, appended at the end of this Report was carried out on the transformation points of these steels, and, in consequence of the results obtained, the temperature of 1000° was adopted for hardening. The heating of the samples was carried out in the bath of salt, and the test-pieces attained the temperature 15 minutes after their introduction into the bath, and were kept at that temperature for a further period of 10 minutes, being subsequently quenched in water at 20°.

### VARIATION OF THE ELECTRICAL RESISTANCE WITH THE PERCENTAGE OF VANADIUM.

1. *Steels containing 0·2 per Cent. of Carbon* (Curves of Fig. 53).—

TABLE XI.

Description of Steel.	Carbon. Per Cent.	Vanadium. Per Cent.	Electrical Resistance in Microns per Cubic Centimetre.		
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.	Increase on Hardening. Per Cent.
1V0·5 . . .	0·13	0·60	14·0	15·7	1·7
1V0·7 . . .	0·14	0·75	15·1	19·9	4·8
1V1 . . . .	0·11	1·04	16·2	21·7	5·5
1V1·5 . . .	0·13	1·54	18·8	21·9	3·1
1V3 . . . .	0·19	2·98	30·1	31·8	1·7
1V4 . . . .	0·38	5·37	31·7	31·6	-0·1
1V7 . . . .	0·13	7·39	33·6	38·4	-0·2

Between 0.6 and 3 per cent. of vanadium the electrical resistance of the normal steels increases very regularly to the extent of 6.7 microhms up to 1 per cent. of vanadium, and more slowly from this amount up to 7.0 per cent. of vanadium. The increase due to the passage into solution of 1 per cent. of vanadium in the iron is, according to the atomic weight of vanadium,  $\frac{26.8 \times 12}{51.2} = 6.2$  microhms, a figure closely agreeing with that found experimentally. It may therefore

———— HARDENED STEELS  
 ..... NORMAL STEELS

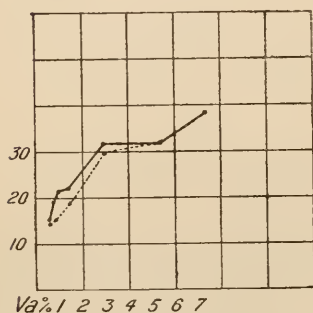


FIG. 53.—Steels containing 0.2 per cent. of Carbon.



FIG. 54.—Steels containing 0.8 per cent. of Carbon.

be said that Benedicks' formula is applicable to those steels up to 3 per cent. of vanadium.

In the case of the hardened steels the curve is less regular; the average increase between 0.6 and 3 per cent. of vanadium is, however, still about 16.1 microhms as in the case of the normal steels.

The increase in the electrical resistance on hardening varies considerably with the percentage of vanadium. The curve shown in Fig. 55 gives the variations in this increase. It may be seen that it is at its maximum for 1 per cent. of

vanadium, and thereafter falls, to become subsequently *nil* with 5 per cent. of vanadium. The increase is 5.5 microhms for the steel with 1.0 per cent. of vanadium, which corresponds with the passage of 0.2 per cent. of carbon into solid solution, a figure almost double that of the total carbon of this steel. It must be concluded from this that heating has produced a dissolution, not only of carbon, but also of part of the vanadium. Hardening should therefore be accompanied, not only by the disappearance of the carbide of iron which occurs in the pearlite, but also of a portion of the pre-existing double carbide of iron and vanadium.

2. *Steels containing 0.8 per Cent. of Carbon* (Curves of Fig. 54).—

TABLE XII.

Description of Steel.	Carbon. Per Cent.	Vanadium. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.		
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.	Increase on Hardening. Per Cent.
8V0.2 . . .	0.82	0.25	21.4	38.2	16.8
8V0.5 . . .	0.72	0.60	21.7	37.7	16.0 (20.5)
8V0.7 . . .	0.89	0.80	22.4	42.6	22.2
8V1 . . . .	0.67	1.15	19.3	31.5	12.2
8V2 . . . .	0.95	2.89	22.5	31.8	11.3
8V5 . . . .	1.08	4.99	20.9	27.6	6.7
8V7 . . . .	0.74	7.85	37.5	37.5	0.0
8V10 . . . .	0.86	10.25	107.2	107.0	0.0

Up to 5 per cent. of vanadium the resistance of the normal steels remains constant, and practically equal to 21 microhms. It then increases very rapidly until it reaches 107 microhms, with 10.25 per cent. of vanadium, which represents, on an average, an increase of over 17 microhms for each per cent. of vanadium. This steadiness in the electrical resistance, followed by a very sudden rise, appears to indicate that, up to 5 per cent. of vanadium, the concentration of the solid solution of iron-vanadium remains steady, the addition of vanadium serving, for the greater part, to increase the amount of carbon present. Above this figure, all the carbon capable of forming carbide under these conditions enters into com-



bination, and the concentration of the solid solution of iron-vanadium increases rapidly, thus occasioning a considerable increase in the electrical resistance.

The electrical resistance of the hardened steels, after having presented a maximum with 0·8 per cent. of vanadium, decreases, and finally becomes equal to that of the normal steels at 8 per cent. of vanadium. If the curve (Fig. 55) be plotted, representing in terms of the percentage of vanadium the increase in the electrical resistance on hardening, there may

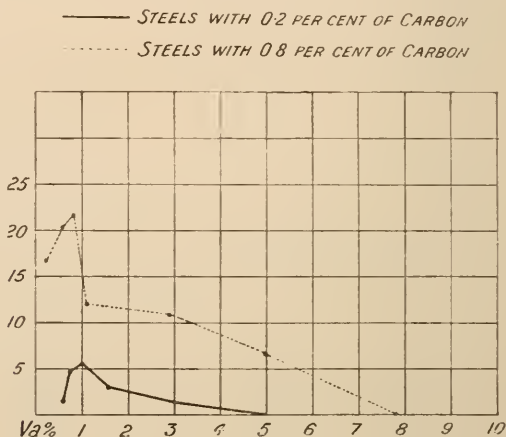


FIG. 55.—Increase in Resistance of Vanadium Steel on Hardening.

be observed a very distinct maximum with 0·8 per cent. of vanadium, followed by a decrease, which is rapid at first and becomes slower. As indicated by the figure in brackets in the last column of Table XII., the value found for the steel 8V0·5 has been corrected, as it contains a lower percentage of carbon than its neighbours. The available quantity of carbide of iron capable of entering into solution in the iron gradually decreases from 0·8 per cent. of vanadium onwards, to become *nil* at 8 per cent. of vanadium.

If the two curves of Fig. 55 be compared with those given by Guillet,\* which represents the influence of hardening on the tensile strength of vanadium steels a great similarity of shape

\* *Les Aciers Speciaux*, vol. ii. pp. 89, 90.

and a remarkable degree of agreement in the positions of the maxima will be observed.

### RELATION BETWEEN THE SPECIFIC RESISTANCE AND THE MICROSTRUCTURE.

1. *Steels containing 0·2 per Cent. of Carbon.*—The micrographic study of the normal steels may be summed up as follows:—

	Vanadium. Per Cent.
1. Pearlitic steels . . . . .	0·0 to 0·7
2. Pearlitic and double carbide steels . . . . .	0·7 to 3·0
3. Double carbide steels . . . . .	over 3·0

The steels hardened at 1000° and etched with picric acid for a period varying from 1 to 2 minutes show martensite and grains of double carbide, which appear very distinct from 5 per cent. of vanadium upwards, but only reveal themselves in small amounts with 3 per cent. of vanadium.

If these results be compared with the data furnished by the investigation on the electrical resistance, it will be seen that the disappearance of the pearlite is marked, on the one hand by a variation in the law of the increase in resistance, and on the other by the influence on this factor of hardening becoming practically *nil*. Besides this, the appearance of carbide from 0·7 per cent. of vanadium upwards in the normal steels, and its disappearance on hardening, up to the steel containing 1·5 per cent. of vanadium, explains the abnormal figure obtained on hardening, for the increase corresponding with 1 per cent. of vanadium as it then enters, owing to this treatment, simultaneously in solid solution of carbon and vanadium. With 5 per cent. of vanadium and upwards, as there is no longer any pearlite, and as the carbon does not diminish on quenching, no further increase in electrical resistance is produced on hardening, as was established by the experiments.

2. *Steels containing 0·8 per Cent. of Carbon.*—The normal steels may be classed, on micrographic examination, as follows:—

	Vanadium. Per Cent.
1. Pearlitic steels . . . . .	0·5
2. Pearlitic and double carbide steels . . . . .	0·5 to 7·0
3. Double carbide steels . . . . .	over 7·0

After hardening, an examination of the surfaces which have been etched by the sulpho-chromic mixture and polished, shows that the carbide appears in isolated and scanty spots, starting with a percentage of 1.15 of vanadium. With lower percentages of vanadium only martensite can be observed, with sometimes a network of troostite. This, as before, explains the occurrence of a maximum in the increase in the electrical resistance on hardening, with 0.8 per cent. of vanadium present, for there is, in this case, a total solution of the pre-existing carbide. The increase is *nil* once the pearlite disappears, and the carbide no longer dissolves on hardening. Further, the regularity of the resistance of normal steels, up to 5 per cent. of vanadium, corresponds well with the fact of the increase in the quantity of carbide with that of vanadium.

From 8 per cent. of vanadium and upwards, as there is no longer any variation in the electrical resistance on hardening, it must be that there exists a solid solution of iron-vanadium, or of vanadium-iron-carbon surrounding the grains of carbide. This solution ought to reveal itself micrographically in the polyhedral form, as in the generality of solid homogeneous solid solutions. It was found possible to develop this structure by employing, as an etching agent, the sulpho-chromic mixture. It is by these means that there may be seen, in Fig. 67, white grains of carbide on a greyish ground, which reveals very clearly defined polygonal lines.

To sum up: the addition of vanadium to steels increases their electrical resistance when it enters into solid solution in the iron, either when, owing to the percentage of available carbon being low, the amount of double carbide that can be formed only utilises a small amount of the vanadium, or, when the percentage of carbon being high, the amount of vanadium is sufficient to absorb the carbon in the state of carbide.

Hardening only produces an increase in the resistance when the normal steel is pearlitic, and this increase reaches its maximum in a steel which contains the highest percentage of vanadium, and in which all the carbide disappears on quenching.

## TITANIUM STEELS.

Nothing has been published on the influence of the introduction of titanium on the electrical resistance of steels and on the transformation points, so that the author was led to complete his investigations by a series of determinations on the critical points of the steels employed. These investigations being somewhat beyond the scope of the present work, the study of the electrical resistance has been consigned to the end of this Report in the form of an appendix.

The two series of steels contained respectively 0.1 per cent. of carbon and up to 2.57 per cent. of titanium, and about 0.6 per cent. of carbon, with, as a maximum, 8.71 per cent. of titanium. (For the analyses of these steels, see p. 278.)

## HARDENING OF THE SAMPLES.

Hardening was carried out at  $950^{\circ}$ , a temperature above that of the highest transformation point of any of the steels studied, as will be seen on reference to Appendix II. to the present Report, which summarises the researches on the heat treatment of steels containing titanium. The conditions of heating were similar to those obtaining in the case of the nickel steels.

## VARIATIONS OF THE RESISTANCE WITH THE PERCENTAGE OF TITANIUM.

The results of the determination of the electrical resistance of the titanium steels are shown in Table XIII.

The first series (steels with 0.1 per cent. of carbon) contained too few steels to allow of accurate conclusions being drawn. It may, however, be seen that the increase in the resistance is 3 microhms for the normal steels, and 3.4 microhms for the hardened steels, when the percentage of titanium rises from 0.42 to 2.57, which corresponds with an average increase of 1.4 microhm for each per cent. of titanium, a figure distinctly lower than that calculated from the atomic weight, which

gives  $26.8 \times \frac{12}{50} = 6.4$  microhms. It cannot, however, be argued from this fact that the titanium is not in solution, for if the electrical resistance of the steel 1Ti0.5 be calculated by means of Benedicks' formula, without taking the titanium into account, we obtain:—

$$7.6 \times 26.8 \left[ 0.112 + \frac{13}{28.4} 0.047 + \frac{12}{55} 0.18 + \frac{12}{32} 0.015 + \frac{12}{31} 0.018 \right] = 12 \text{ microhms.}$$

Now, as the resistance of the hardened steel is 13.6 microhms, the increase due to the presence of 0.42 per cent. of titanium is 1.6 microhm, which comes to 3.4, a figure appreciably higher than that found with higher percentages of titanium. It must therefore be concluded that Benedicks' formula does not apply except in the case of very small percentages of titanium, and that the incremental increase soon ceases.

TABLE XIII.—*Titanium Steels. Temperature 18°.*

Description of Steel.	Carbon. Per Cent.	Titanium. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
I. Steels with 0.1 per Cent. Carbon.				
1Ti0.5 . . .	0.11	0.42	13.1	13.6
1Ti1 . . .	0.11	0.88	13.8	14.3
1Ti2 . . .	0.14	1.40	15.1	15.5
1Ti3 . . .	0.14	2.57	16.1	17.0
II. Steels with 0.6 per Cent. Carbon.				
8Ti0.5 . . .	0.76	0.32	19.8	32.9 (29.3)
8Ti1 . . .	0.70	0.64	21.0	32.3 (30.3)
8Ti2 . . .	0.62	0.72	21.4	31.0
8Ti3 . . .	0.61	2.57	22.2	31.5
8Ti5 . . .	0.63	4.63	25.1	34.3
8Ti10 . . .	0.65	8.71	28.7	37.9

In the second series (steels containing 0.6 per cent. of carbon) anomalous results are noticeable in regard to the two first steels, which give a higher electrical resistance than



those which follow in the case of the hardened steels, whereas the increase, in the case of the normal steels, is regular. This indicates a higher percentage of carbon than the average, which is what the analyses actually reveal. If the results for the hardened steels be rectified by calculating them on a percentage of 0.63 of carbon, the figures shown in brackets in the table, and the increase in the electrical resistance of the hardened steel then becomes regular, and can be expressed as 0.4 microhm by means of the formula—

$$\rho = 29.4 + x,$$

where  $x$  is the percentage of titanium. The co-efficient of the increase in electrical resistance thus becomes 1 microhm for each per cent. of titanium, a figure closely resembling that found for the first series.

If the results of the four last steels of the second series be examined without rectification, it will be found that the divergence between the electrical resistance of the hardened steels and that of the normal steels is 9.4 microhms  $\pm$  0.2 microhm, which corresponds with the passage into solution of 0.35 per cent. of carbon.

As the percentage of carbon in these steels is  $0.63 \pm 0.02$ , it must be that the steels contain, in the normal state, 0.28 per cent. of carbon in solid solution, a figure practically identical with that found by Mr. Benedicks in the case of ordinary carbon steels. Titanium does not, therefore, influence the co-efficient of the solubility in iron so far as the annealed steels are concerned.

The practically constant divergence between the electrical resistance of the hardened steels and that of the normal steels allows of the results found for the latter being expressed by the linear formula:—

$$\rho = 20 + x.$$

The micrographic examination of these steels shows that they are pearlitic in the normal state and martensitic in the hardened state. No alteration of structure can, therefore, be detected with increasing percentages of titanium, and this fact is in perfect harmony with that of the regular increase in the electrical resistance.



Titanium steels containing 0.1 per cent. of carbon reveal martensite with alternating dark and light areas corresponding with facets possessing varying planes of incidence.

### BORON STEELS.

Determinations of electrical resistance were carried out on five boron steels hardened at 950°. The results are shown in the following table, and the analyses are given in the table on p. 279.

TABLE XIV.—*Hardened Boron Steels. Temperature, 25°.*

Description of Steel.	Carbon, Per Cent.	Boron, Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.
<i>Series I.</i>			
2B0.2. . . . .	0.18	0.21	17.1
2B0.5. . . . .	0.22	0.48	22.9
2B1 . . . . .	0.21	0.84	29.0
<i>Series II.</i>			
5B0.2. . . . .	0.47	0.15	29.1
5B0.5. . . . .	0.59	0.41	29.8

It will be seen that the three steels of Series I. contain proportions of manganese and silicon which increase to an important extent with the increasing percentages of boron, and it is not possible, considering the relatively small percentages of boron present, to attribute the marked increase in the electrical resistance, 11.9 microhms, as due to the introduction of the latter element in the steels.

If, indeed, the increase in the resistance be calculated according to Benedicks' formula, from the variation in the percentages of carbon, silicon, and manganese, between the steels 2B0.2 and 2B1 there will be found—

$$\left[0.03 + 0.56\frac{12}{28.4} + 0.53\frac{12}{55}\right]26.8 = 10.2 \text{ microhms.}$$

There is thus an increase, in reality, of only 1.7 microhms during the rise from 0.21 to 0.84 per cent. of boron, which

represents an increase of 2·7 microhms due to the presence of a per cent. of boron, a figure differing very greatly from that calculated from the atomic weight:—

$$26\cdot8 + \frac{12}{11} = 29\cdot2 \text{ microhms.}$$

It must therefore be concluded that in the steels under investigation the boron is not in solid solution even after hardening. This assumption is confirmed on comparing the steels 5B0·2 and 5B0·5.

The micrographic study of these steels shows that after etching by picric acid, there is, in addition to martensite, a special constituent which colours black with sodium pierate similarly to cementite, and is, according to Guillet, a borocarbide of iron. In any case it appears to be beyond doubt, given the low incremental increase in the electrical resistance, that boron enters into the composition of this special constituent, and that the percentage of boron in solid solution which surrounds it varies but little within the limits found in the samples in question.

### TANTALUM STEELS.

The results obtained with tantalum steels, which are summarised in the following table, do not admit of the deduction of any conclusions. The increase in the electrical resistance is very small and irregular, the estimated increase calculated from the atomic weight being, for a per cent. of tantalum, but small in itself. (For analyses, see p. 279.)

TABLE XV.—*Tantalum Steels. Temperature, 25°.*

Description of Steel.	Carbon. Per Cent.	Tantalum. Per Cent.	Electrical Resistance in Microhms per Cubic Centimetre.	
			Normal Steels. Per Cent.	Hardened Steels. Per Cent.
2Ta0·2 . . .	0·12	0·00	14·1	14·4
2Ta0·5 . . .	0·17	0·15	14·6	14·8
2Ta1 . . . .	0·18	0·6	14·8	15·1
2Ta2 . . . .	0·16	0·05	14·8	15·2

## GENERAL CONCLUSIONS.

The most significant fact that appears to be the outcome of these investigations is that the laws as to the variation in the specific electrical resistance of the ternary steels, with the amount of the added element, undergo fairly sudden changes corresponding with alterations in the microstructure, and that

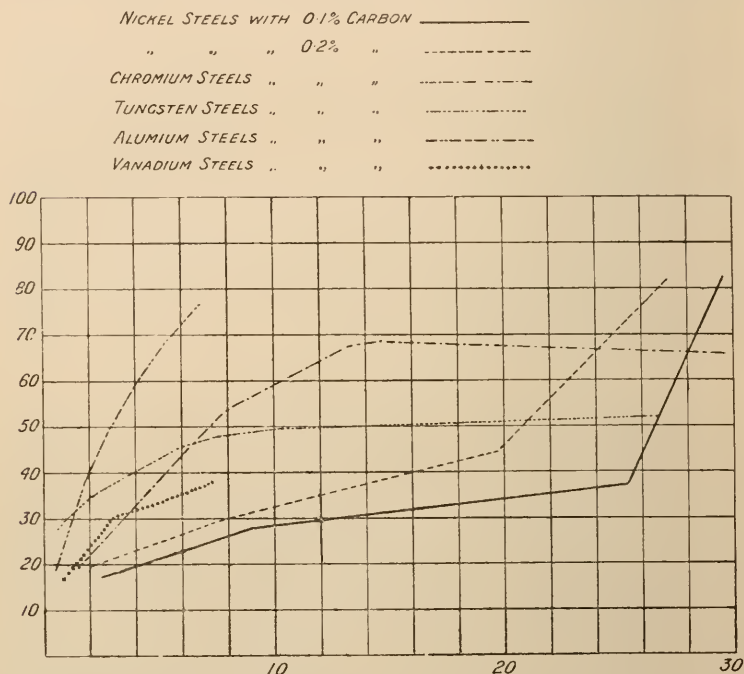


FIG. 56.—Influence of Different Elements on the Electrical Resistance of Steel.

if these laws be plotted as curves they can, generally speaking, be separated into a certain number of rectilinear portions, the weak curvature of each of which is characteristic of a definite micrographic condition of the steel, pearlitic, martensitic, polyhedral, or accompanied by the appearance of a double carbide.

The curves shown in Figs. 56 and 57 give the general

NICKEL STEELS WITH 0.8% CARBON .....  
 " " HARDENED .....  
 CHROMIUM STEELS WITH 0.8% CARBON .....  
 " " HARDENED .....  
 TUNGSTEN STEELS WITH 0.8% CARBON .....  
 " " HARDENED .....

ALUMIUM STEELS WITH 0.8% CARBON .....  
 " " HARDENED .....  
 VANADIUM STEELS WITH 0.8% CARBON .....  
 " " HARDENED .....  
 TITANIUM STEELS WITH 0.8% CARBON .....  
 " " HARDENED .....

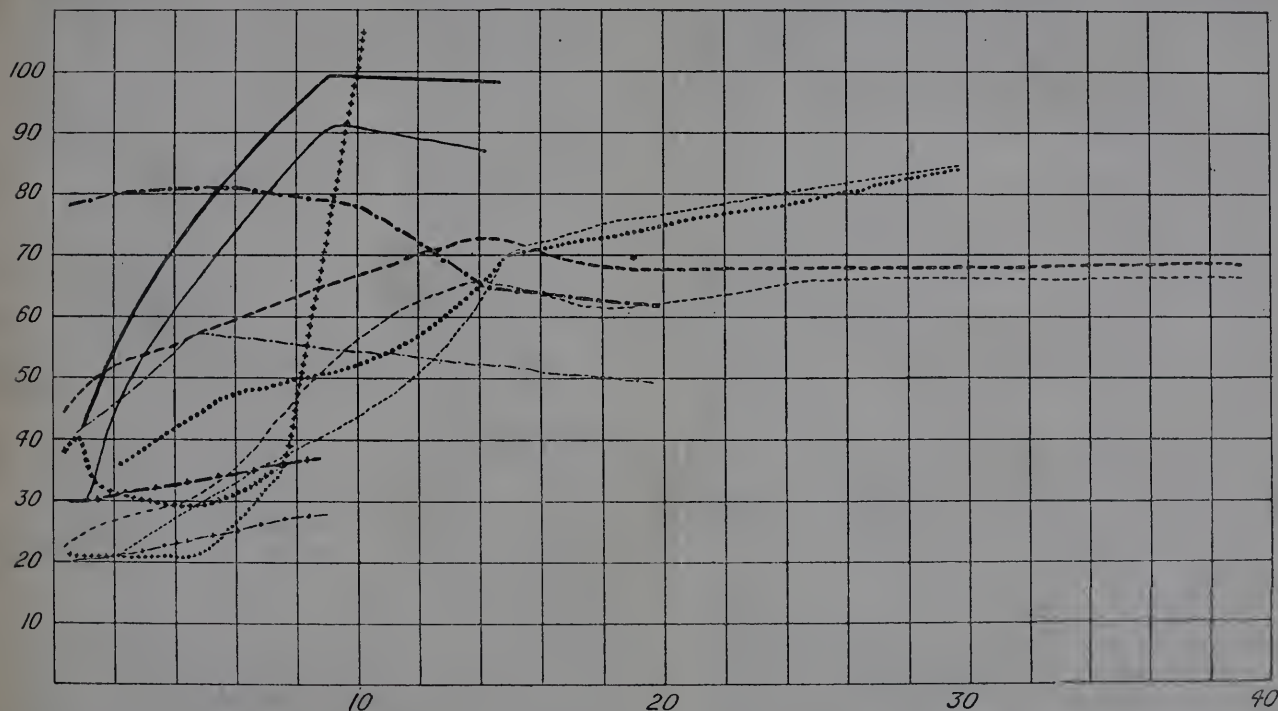


FIG. 57.—Influence of Different Elements on the Electrical Resistance of Steel.



characteristics for steels with low percentages of carbon. Only the electrical resistance of the normal steels has been shown as the variations consequent on hardening are often so small that it would be difficult graphically to represent them on the scale of the drawing. For steels containing 0·8 per cent., on the other hand, curves relating both to the normal and to the hardened steels have been traced.

If to the study of the variations in the electrical resistance of steels consequent on the introduction therein of different elements be added that of the variations resulting from quenching those steels, it is possible to distinguish, generally speaking, the following microstructural types :—

1. *Pearlitic Steels*.—The resistance increases steadily with the increase in the percentage of the added element, and may be represented in terms of the latter factor, by a linear formula, or by a parabolic formula the co-efficient of the squared term of which is small (aluminium steels). On quenching they undergo an increase corresponding with the passage into solid solution of the available carbon of the carbide. It was possible, in most instances, to verify the fact stated by Benedicks, that steels with about 0·8 per cent. of carbon in the normal state contain about 0·27 per cent. of their carbon in a state of solid solution. The presence of certain elements, such, for instance, as molybdenum, appear to modify the latter figure.

2. *Martensitic Steels*.—The increase in the electrical resistance with that in the percentage of the special element is smaller than in the case of the pearlitic steels.

The variation in the resistance on hardening is practically *nil* for the steels containing a low percentage of carbon, as may be very clearly seen with pearlitic steels containing the same percentage of carbon. For the martensitic steels with 0·8 per cent. of carbon there is found an increased electrical resistance on hardening, the importance of which decreases in proportion as the percentage of the special element becomes higher. Not all the carbon of the martensitic steels is therefore in solution. This fact corresponds, likewise, with the hardening on quenching, of the martensitic steels which is seen, in particular, as regards those which border closely on the pearlitic steels.



3. *Polyhedral Steels*.—The polyhedral steels are distinguished by a rapid rise in the electrical resistance, with the rise in the percentage of the added element. On hardening they undergo no variation, or only a slight diminution. This diminution corresponds with the appearance of martensite, in lanceolate crystals, and occurs in steels which border closely upon the martensitic class.

4. *Double Carbide Steels*.—Two conditions may be distinguished:—

(a) The addition of the special element betrays itself by an increase in the amount of carbide (chromium and tungsten steels and vanadium steels with 0.8 per cent. of carbon and less than 5 per cent. of vanadium), while the electrical resistance remains practically constant or undergoes but slight increase.

(b) With increasing proportions of the special element the amount of carbide varies but slightly (vanadium steels with low percentages of carbon and vanadium and steels with 0.8 per cent. of carbon and over 7 per cent. of vanadium), and there is then seen a notable increase in the electrical resistance which corresponds with the increased concentration of the solid solution surrounding the carbide.

The variation in the resistance on hardening depends both on the nature of the constituent which surrounds the carbide, and on the solvent capacity of this carbide. The pearlitic steels and those containing the carbide undergo an increase in their electrical resistance on hardening, corresponding with that of the ordinary pearlitic steels, to which has, at times, to be added that which results from the solution of the carbide (vanadium steels). Steels with a martensitic basis display a smaller increase in electrical resistance on hardening than those of the preceding category.

Steels consisting mainly of a solid solution do not, generally speaking, undergo any change on hardening. It is necessary in this connection to point out that the solution of carbon on hardening depends on all the phases of the heat treatment; temperature of heating; duration of heating; rate of cooling, and rate of traversing the critical point. It is not possible, therefore, definitely to pronounce upon the influence of this treatment on the electrical resistance, except after experiments

in which these different factors had been varied. This the author hopes to do in a study of the solution of iron carbides, and of double carbides, on hardening. This research will be carried out on a certain number of types of hypereutectic carbon steels and special steels containing the double carbide. From what has been said it will be seen that Benedicks' law which expresses lineally the variation of the electrical resistance in terms of the percentages of the elements in solid solution in the iron can only be applied in the case of low percentages of the special element. The limits of its applicability may, in the case of steels containing low carbon percentages (0·2 per cent.), be fixed approximately as follows:—

	Limit. Per Cent.
Nickel steels . . . . .	<2·0
Chromium steels . . . . .	<1·0
Tungsten steels . . . . .	7·0
Aluminium steels . . . . .	1·0
Molybdenum steels . . . . .	5·0
Vanadium steels . . . . .	3·0
Titanium steels . . . . .	<0·5
Boron steels . . . . .	<0·2

Below these amounts the increase in the electrical resistance for each per cent. of the element added agrees in a satisfactory manner with that calculated from the formula—

$$26·8 \frac{12}{Pa}$$

where  $Pa$  is the atomic weight of the added element, but, in any case, Benedicks' formula appears chiefly to be a limitational formula to which we approach whenever the percentage of the added element decreases. It is the equation of the tangent to the commencement of the curve representing the electrical resistance in terms of the percentage of the special element.

### ELECTRICAL RESISTANCE AND CONDUCTIVITY.

An attempt might have been made to study the electrical conductivity instead of the electrical resistance, as was done by Guertler, in the case of alloys, but it may be pointed out that

in each structural zone the curve of resistance is practically a straight line, and could therefore be expressed in terms of the percentage  $x$  of the element added to the steel by means of the formula—

$$\rho = ax + b.$$

The specific conductivity would therefore be, in this case

$$\gamma = \frac{1}{ax + b}$$

the equation of an equilateral hyperbola of which the asymptotes are one of the axes of the abscissæ and of the perpendicular produced to this axis through the point where it is met by the straight line representing the electrical resistance.

The curves of the electrical conductivity would therefore be, generally speaking, made up of a certain number of the branches of the hyperbola, and the laws of variation would consequently be much more difficult of deduction than from a study of the resistance.

### ELECTRICAL RESISTANCE AND HARDNESS.

Kurnakov and Zemczuzny, in a recent article,\* have shown that in solid metallic solutions there is a certain relation between the electrical resistance and the hardness, these two qualities varying usually in the same proportion. Without embarking on this subject it is of interest to compare the curves of resistance given in the present work with those of hardness ascertained by the Brinell method, published by Guillet.†

It will be seen, on such a comparison, that while the curves present, in their general characters, an air of family likeness, notably in the case of chromium steels, tungsten steels containing 0·8 per cent. of carbon, and aluminium steels with 0·2 per cent. of carbon, there may also be observed notable points of difference, particularly in the case of nickel steels.

\* "Die Härte der festen Metallösungen und au bestimmten chemischen Verbindungen," *Zeitschrift für Anorganisches Chemie*, vol. lx., October 1908.

† *Les Aciers Spéciaux*. Paris: Dunod, 1905.

It would appear reasonable to admit that these two physical qualities, electrical resistance and hardness, are functions of a large number of variable factors, and that amongst those variable factors there are certain common ones the influence of which, when not masked by that of others, reveals itself by a correspondence in the appearance of the curves of the variations in resistance and hardness.

To sum up: the investigation of the electrical resistance appears more complex in the special steels by reason of the microstructures which they possess, and, generally speaking, it helps to confirm the results obtained by a micrographic examination of these steels. Nevertheless it affords a further means of distinguishing their properties as it reveals modifications which a micrographic examination would fail to show, particularly as regards the influence of hardening.

It would afford great assistance in the latter instance, when it is desired to define the factors taking part in the treatment. From a practical point of view it has the advantage of allowing a series of experiments to be made on the same test-piece without destroying the latter, and, therefore, of experimenting on a material the composition of which remains strictly the same. It is unnecessary to emphasise the great importance of this fact in an investigation of the result of heat treatment, and on these grounds alone a study of the electrical resistance deserves to take its place side by side with the other methods of investigation employed in researches on the alloys of iron.

## APPENDIX I.

### INFLUENCE OF VANADIUM ON THE TRANSFORMATION POINTS OF STEEL.

The only investigations made on the determination of the critical points of vanadium steels are those of Pultz,\* who studied steels containing up to 0.98 per cent. of vanadium

\* Pultz, "Der Einfluss des Vanadiums auf Eisen und Stahl," *Métallurgie*, vol. iii., 1906, p. 649; *Bestimmung der Kritischen Punkte*.

and whose conclusions on the subject may be summed up as follows:—

1. A small addition—0·2 per cent.—of vanadium suffices to raise the point  $Ar_1$  by nearly  $10^\circ$ , without a further addition of vanadium having as a result the further raising of this point.

2. The point  $Ar_{3,2}$  is also raised, but, in contrast to point  $Ar_1$ , it rises proportionately to the percentage of vanadium.

It appears difficult to determine accurately this  $10^\circ$  limit of rise with 0·2 per cent. of vanadium, as it would be necessary to compare extra pure steels containing 0·0 and 0·2 per cent. of vanadium respectively.

In their research on the ferro-vanadium alloys, Vogel and Tammann\* have not ascertained the transformation points of the solid solutions formed by these alloys, and in the present work the author has confined himself to comparing the critical temperatures of two series of vanadium steels containing from 0·2 to 7·0 per cent. of vanadium, and about 0·2 and 0·8 per cent. of carbon.

*Experimental Arrangements.*—The determination of the critical points was made by employing the differential method of Roberts-Austen by means of a double Saladin-Le Chatelier galvanometer. The sample, in the form of a small block, measuring  $10 \times 12 \times 15$  millimetres, was placed in a Héräus furnace, together with the sample of nickel steel, which served as a basis for comparison. In order to study the heating curves, the electrical heating of the furnace was effected by means of a progressive electrical liquid resistance with an automatic siphon stop, an arrangement already described elsewhere by the author.† It possesses the advantage of affording an exceedingly regular heating, the liquid resistance being fed by the water running from a Mariotte vessel, and of being perfectly automatic, the whole appliance being capable of being left to itself directly it has been started.

It is absolutely necessary, in order to avoid the oxidation of the samples, to work in an atmosphere of inert gas. With this object there was employed a slow current of commercial

\* *Zeitschrift für Anorganische Chemie*, vol. lviii. pp. 73–82.

† *Revue de Métallurgie*, 1908, p. 302.



nitrogen, previously freed from the slight traces of oxygen which it contained by passing it over heated copper turnings. This notwithstanding, it was impossible to avoid a superficial decarburisation of the samples extending at times to a depth of 0.3 millimetre. This decarburisation reveals itself in the curves relating to the steel containing 0.8 per cent. of carbon by a slight break in the vicinity of  $850^{\circ}$ , which characterises the point  $Ar_3$  in the steels with a low percentage of carbon.

This break may be noticed in Fig. 60, and this source of error is frequent. It is from this cause that Carpenter and Keeling observed critical points in the vicinity of  $800^{\circ}$ , which were due, in reality, to the point  $Ar_2$  of the curve relating to the exterior of the samples.\*

The standardisation of the thermo-couple was made by means of the melting-points of gold  $\dagger$  ( $1064^{\circ}$ ), silver  $\ddagger$  ( $932^{\circ}$ ), and of antimony  $\S$  ( $630.6^{\circ}$ ), and by the boiling-point of naphthalene ( $218^{\circ}$ ).

This standardisation was frequently repeated, as the platinum wire undergoes changes and breaks, and considerable differences are found in the deviations. Owing to this the space occupied per  $100^{\circ}$ , in the neighbourhood of  $900^{\circ}$ , varied in the series of experiments from 16 millimetres to 14.5 millimetres.

The records of the evolutions of heat which can be made by the differential method, as the author has indicated, || when recalescence occurs, have only been utilised in a few isolated instances in the present work, as it necessitates very careful standardisation of the differential system found by the two opposing couples.

On each steel two to six determinations were carried out so as to eliminate the accidental anomalies which are so often observed in using the automatic differential method, due, amongst other causes, to vibrations and to accidental contact of the wires owing to defective insulation at some point.

\* A. Portevin, "Etat actuel des theories sur l'équilibre du système Fer-Carbone," *Revue de Métallurgie*, vol. iv. p. 993.

$\dagger$  Berthelot, *Comptes Rendus*, vol. cxx. p. 831.

$\ddagger$  Harker, *Electrochemical and Metallurgical Industry*, vol. v. p. 48.

$\S$  Holborn and Day, *Annales de Physique*, Series IV. vol. ii. p. 535.

|| *Revue de Métallurgie*, vol. v. p. 295.



Despite the precautions there will be noticed in the results given later, particularly as regards steels with high percentages of vanadium, irregularities which must chiefly be attributed to differences in composition due to the segregation of carbide.

1. *Steels containing 0.2 per. Cent. of Carbon.*—Table XVI. gives, in terms of the percentage of vanadium, the temperatures of the breaks observed on the heating and cooling curves. The temperatures indicated are those at the commencement of the breaks, that is to say, that they mark the commencement of the absorption or evolution of heat due to the transformation.

TABLE XVI.—*Vanadium Steels with 0.2 per Cent. of Carbon.*

Description of Steel.	Vanadium. Per Cent.	Heating. 0° C.	Cooling. 0° C.		
1Va0.5 . . . . .	0.60	810	905	810	730
1Va0.7 . . . . .	0.75	810	895	810	730
1Va1 . . . . .	1.04	795	920	805	690
1Va1.5 . . . . .	1.54	800	945	800	...
1Va2.3 . . . . .	2.98	840	950	830	...
1Va4 . . . . .	5.37	812	960	815	...
1Va7 . . . . .	7.39	860	?	840	590
1Va10 . . . . .	10.27	?	...	820	570

Apart from the points indicated on heating, which are, moreover, not particularly clearly defined, there may be observed, between 740° and 760°, slight evolutions of heat the causes of which have not been ascertained.

As may be seen from the table, the steels very rich in vanadium (1Va7 and 1Va10) furnish, below 600°, an evolution of heat which is indicated by a thickening of the curve for an interval of about 50°.

The point Ar<sub>1</sub> is but slightly noticeable in these steels with low carbon percentages, and could only be seen in the first three steels of this series. It is not possible, therefore, to draw any conclusions as to the influence of vanadium in this case, besides which, light can be thrown on the subject by studying the series of steels containing 0.8 per cent. of carbon. Points Ar<sub>3</sub> and Ar<sub>2</sub> appear to rise progressively with the proportion of vanadium present.

2. *Steels containing 0·8 per Cent. of Carbon.*—In this series the author limited himself to ascertaining the recalescence points on heating and on cooling, these points being indicated by practically horizontal parts of the curve, and the temperatures being therefore determined without any ambiguity.

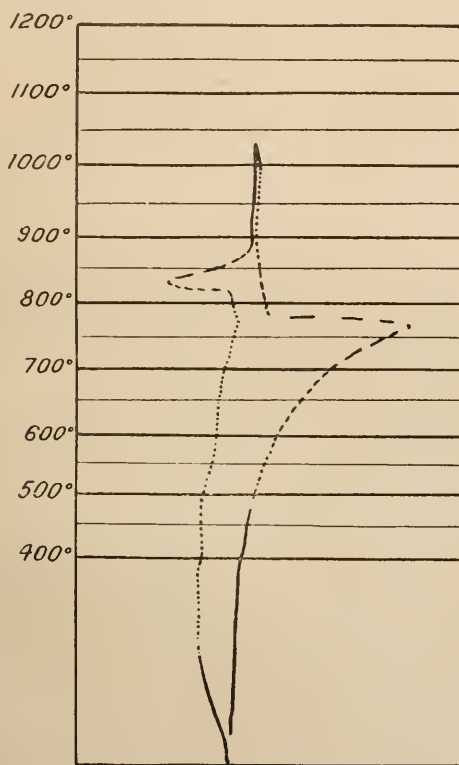


FIG. 58.

There will likewise be seen, in the heating curve, a slight bend between  $750^{\circ}$  and  $790^{\circ}$ , which thus precedes the recalescence. This occurrence may be observed in the cooling curves of Figs. 58 and 59, relating respectively to steels 8Va0·5 and 8Va0·7. When the sample is heated to a temperature sufficiently high, about  $1200^{\circ}$  (Fig. 59), it will be seen

that recalescence is preceded by a very slow progressive deviation, the ill-defined commencement of which occurs between  $800^{\circ}$  and  $850^{\circ}$ . If the heating be carried to  $1000^{\circ}$  only (Fig. 58) this appearance is not, generally speaking, met with,

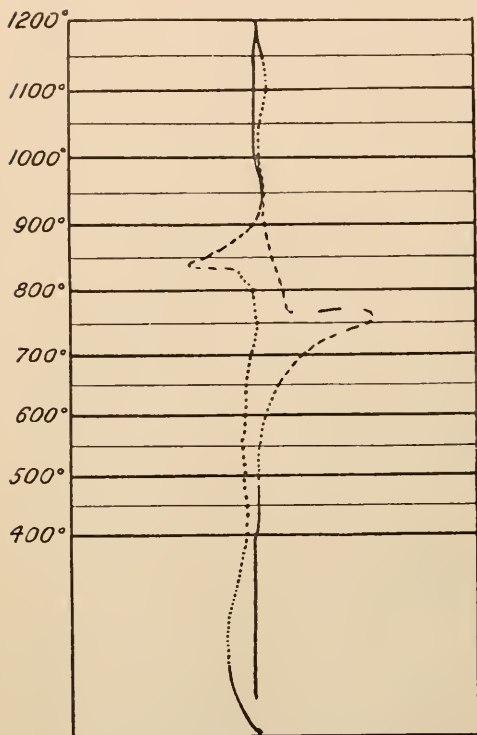


FIG. 59.

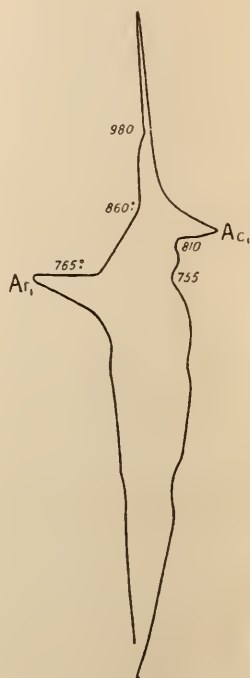


FIG. 60.—Differential Curves of Steel 8Ti2.

or else occurs to so slightly appreciable an extent as to escape notice.

In Table XVII. have been given the recalescence temperatures and the percentages in vanadium of the steels experimented upon. It will be seen that up to 1 per cent. of vanadium the critical temperatures remain very nearly constant, whereas they fall with the percentage of vanadium as soon as this limit of 1 per cent. becomes exceeded.

TABLE XVII.—*Vanadium Steels with 0·8 per Cent. of Carbon.*

Description of Steel.	Vanadium. Per Cent.	Bend in Curve on Heating. Degrees.	Recalescence on Cooling. Degrees.
8Va0·2 . . . . .	0·25	800	740
8Va0·5 . . . . .	0·60	800	738
8Va0·7 . . . . .	0·80	800	740
8Va1 . . . . .	1·15	798	740
8Va1·5 . . . . .	1·58	785	732
8Va2 . . . . .	2·89	790	730
8Va5 . . . . .	4·99	782	720
8Va7 . . . . .	7·85	780	700

## APPENDIX II.

## INFLUENCE OF TITANIUM ON THE TRANSFORMATION POINTS OF STEEL.

No determinations of the critical temperature of titanium steels have been published, and the author therefore undertook this investigation in order to ascertain what influence the introduction of titanium in a steel might have on the position of the transformation points.

The experimental appliances employed were identical with those described previously, with regard to vanadium steel. Similarly, at least two determinations were made on each sample.

1. *Steels containing 0·6 per Cent. of Carbon. Influence of Titanium on the Recalescence Points  $Ac_1$  and  $Ar_1$ .*—In the steels with 0·6 per cent. of carbon the recalescence point reveals itself very distinctly in the curves obtained by the differential method as it assumes the form of a well-marked horizontal hook. Fig. 60 affords an example (steel 8Ti12). In addition to the occurrence of points  $Ac_1$  and  $Ar_1$  there may also be seen the thickening of the heating curve at 755, which is found in nearly the whole of the curves of this series as had been already observed in certain vanadium steels. On the cooling curve there may be noted the very slight extension

of heat at  $980^{\circ}$ ,\* which characterises the point  $Ar_3$  of the outer decarburised layer. Below this the curve shows a gradual evolution of heat commencing from  $860^{\circ}$ , which marks the beginning of the interval  $Ar_{3.2} - Ar_1$ ; but the commencement of this interval being somewhat ill defined, it was decided, in preference, to study the influence of titanium on the points  $Ar_3$  and  $Ar_2$  by operating on steels with low percentages of carbon, and to reserve those containing 0.6 per cent. of carbon for the examination of the recalescence point.

The following results were obtained:—

TABLE XVIII.—*Recalescence Points of Titanium Steel containing 0.6 per Cent. of Carbon.*

Description of Steel.	Titanium, Per Cent.	Transformation Point—	
		On Heating. $Ac_1$ . Degrees.	On Cooling. $Ar_1$ . Degrees.
8Ti0.5 . . . . .	0.32	755	716
8Ti1 . . . . .	0.64	800	765
8Ti2 . . . . .	0.72	810	765
8Ti3 . . . . .	2.57	812	765
8Ti5 . . . . .	4.63	825	765
8Ti10 . . . . .	8.71	828	768

It will be seen that the point  $Ac_1$  rises somewhat suddenly up to 0.6 per cent. carbon and subsequently rises slowly with the increase in the percentage of titanium (about  $3^{\circ}$  rise for each per cent. of the latter) and that  $Ar_1$  also undergoes a sudden rise at 0.6 per cent. of titanium and subsequently remains constant at  $765^{\circ}$ .

2. *Steels containing 0.1 per Cent. of Carbon. Variation of the Points  $Ar_3$  and  $Ar_2$ .*—On heating, the results are not very clearly defined. A break is noted at about  $740-750^{\circ}$ , and undulations occur above, in the curve. On cooling the three

\* This temperature of  $980^{\circ}$  is distinctly higher to that which corresponds with the transformation point of the exterior layer of metal with a very low carbon percentage, owing to the difference in temperature which exists between the centre and the surface of the sample, a difference which depends on the rate of cooling of the whole piece, and on the rate of the transmission of heat in the steel.

critical points of steels with low percentages of carbon, but the transformations being gradual the breaks are rounded off. With the object of facilitating the reading of these curves they have been transformed into what Mr. Rosenhain describes as "derived differential curves": that is to say, into curves giving, in terms of the temperature, the variations of the deviation of the differential galvanometer corresponding to a similar fall in temperature. Figs. 61 and 62 represent the curves traced by the differential galvanometer, and those derived therefrom, for



FIG. 61.—Cooling Curves of Steel 1Ti0.5.



FIG. 62.—Cooling Curves of Steel 1Ti2.

steels 1Ti0.5 and 1Ti2. There are then seen very distinctly three points on the latter curves, and by adopting their temperatures as the points of transformation the figures given in Table XIX. are obtained.

It may thus be seen that  $Ar_3$  is lowered by the addition of titanium, whereas  $Ar_2$  and  $Ar_1$  are not affected. Besides this, between  $620^\circ$  and  $580^\circ$  evolutions of heat occur. These are very slight, it is true, but their cause is unknown.

3. *Remarks on the Derived Differential Curves.*—The method which has been employed (derived differential curves) is to



the Roberts-Austen differential method what the Osmond method (curves of the inverse rates of cooling) is to the ordinary curves giving the temperatures in terms of the rates.

TABLE XIX.—*Transformation Points of Titanium Steels containing 0.1 per Cent. of Carbon.*

Description of Steel.	Titanium. Per Cent.	Transformation Point.		
		Ar <sub>3</sub> . Degrees.	Ar <sub>2</sub> . Degrees.	Ar <sub>1</sub> . Degrees.
1Ti0.5 . . .	0.42	860	780	690 ...
1Ti1 . . .	0.88	850	780	690 610
1Ti2 . . .	1.40	830	780	690 580
1Ti3 . . .	2.57	830	780	690 620

It may be asked whether this method, of comparatively recent introduction, gives the same temperatures as Osmond's method which served for the earliest determinations of the critical points of steels, and was subsequently employed to obtain the figures which have been taken as a basis for reference in the comparisons one is led to make between the different steels.

1. In Osmond's method there is plotted, in terms of the temperature of the steel sample, the time required for this temperature to fall a certain number of degrees. It is, in the last resource, a curve giving, in terms of the temperature, the variations in the inverse ratio of the rate of cooling. The critical temperatures are those corresponding with the maxima rates of cooling.

Now, if  $t = f(z)$ ,  $z$  indicating the time, be the ordinary cooling curve, the curve of the inverse rate will be

$$\frac{dz}{dt} = \phi(t).$$

It will display a maximum when

$$\frac{dt}{dz}$$

is a minimum and

$$\frac{d^2t}{dz^2} = 0$$

is then the result. The critical temperatures correspond,

therefore, with the bending points of the temperature-time curve.

2. In the Roberts-Austen differential method the cooling curve  $t=f(z)$  of the sample is compared with the cooling curve  $t_1=f_1(z)$  of a standard sample placed under similar conditions and not undergoing any transformation. This comparison is effected by plotting point by point, or automatically the curves  $t=F(x)$  with the curve  $x=t-t_1$ .

In the method recommended by Rosenhain, which he has called the "derived differential curve," the curve obtained is formed by plotting, for each temperature, the variation undergone by the factor  $t-t_1$ ; that is to say, the deviation of the differential galvanometer during the same temperature interval. This is, in the limit, the curve which gives the variation, in terms of the temperature, of the inverse of the derived

$$\frac{dF}{dx}$$

of the differential curve. As before, the critical temperatures, which are marked by the minima of the derived differential curve, will correspond to the points of inflexion of the curve  $t=F(x)$ . There will thus again be *nil* with the second derived

$$\frac{d^2F}{dx^2}$$

Now, it can readily be seen that

$$\frac{d^2F}{dx^2} = \frac{\frac{d^2t}{dz^2} \frac{dt_1}{dz} - \frac{d^2t_1}{dz^2} \frac{dt}{dz}}{\left(\frac{dt}{dz} - \frac{dt_1}{dz}\right)^2}.$$

In Osmond's method, at the critical points marked by the curve we have

$$\frac{d^2t}{dz^2} = 0,$$

and in Rosenhain's method, at the critical points we have

$$\frac{d^2F}{dx^2} = 0.$$

In order that the temperature found should be the same there must therefore be, for the same value of  $t$ :

$$\frac{d^2t}{dz^2} = 0 = \frac{d^2F}{dx^2},$$

simultaneously. The preceding formula shows that to satisfy this condition we must have either

$$\frac{d^2t}{dz^2}=0,$$

or

$$\frac{dt}{dz}=0.$$

Now

$$\frac{d^2t_1}{dz_2} > 0,$$

as the standard sample, not undergoing any transformation, its

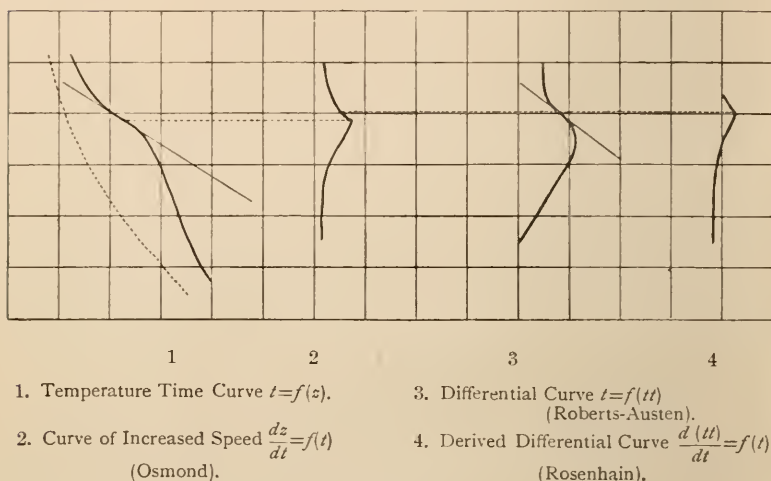


FIG. 63.

cooling curve cannot show any points of inflexion. There would therefore only be agreement when

$$\frac{dt}{dz}=0,$$

that is to say, if the tangent of the curve temperature + temperature-time be horizontal. In this case the curves of Osmond and of Rosenhain will show an infinitely distant point.

Fig. 63 represents graphically that which has just been ascertained by calculation. The left-hand curves represent the ordinary cooling curves of the standard sample (dotted

curve), and of the sample which has undergone a transformation, indicated by a bending point. By means of these curves three others have been plotted corresponding with the



FIG. 64.—Steel with 0.8 per cent. Carbon and 15 per cent. Nickel; hardened at  $975^{\circ}$ ; etched with picric acid ( $1\frac{1}{2}'$ ). Magnified 200 diameters. Martensite and Polyhedrons.

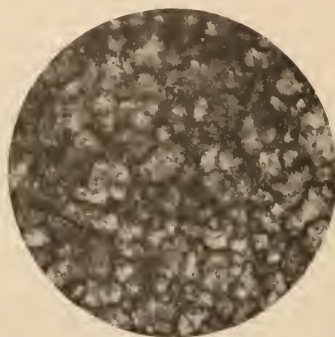


FIG. 65.—Steel with 0.8 per cent. Carbon and 10 per cent. Chromium; hardened at  $980^{\circ}$ ; etched with sulpho-chromic mixture ( $3'$  at  $50^{\circ}$ ). Magnified 200 diameters. Black network of troostite.



FIG. 66.—Steel with 0.1 per cent. Carbon and 0.9 per cent. Titanium; hardened at  $970^{\circ}$ ; etched with picric acid ( $3'$ ). Magnified 200 diameters. Martensite.

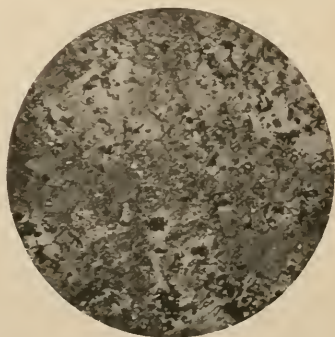


FIG. 67.—Steel with 0.86 per cent. Carbon and 10.2 per cent. Vanadium; hardened at  $1000^{\circ}$ ; etched with sulpho-chromic mixture ( $3'$ ). Magnified 200 diameters. Double carbide and solid solution of ferrite and vanadium.

three methods of Osmond, Roberts-Austen, and Rosenhain, and there may be seen a difference of temperature between the points in the curve of the inverse rate, and those of the derived differential curve.

It appears advisable to emphasise this point as, up to the present, there does not seem to have been any comparisons made, on this subject, between the three different methods.

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